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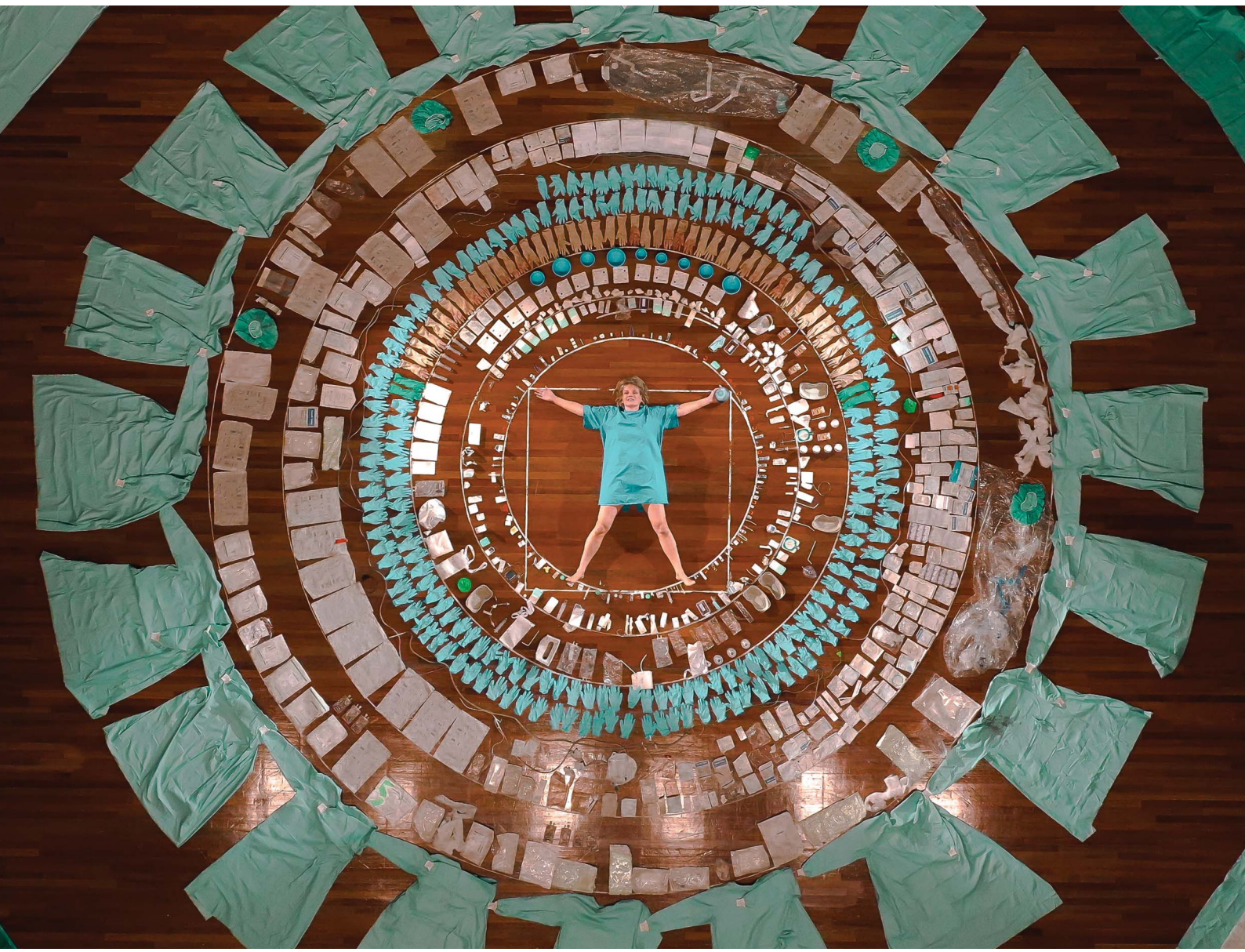

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CRITICAL REVIEW
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Biodegradable bioplastics in healthcare: opportunities, challenges and sustainable recycling

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The healthcare sector ranks among the largest consumers of single-use plastics, generating substantial amounts of waste, an issue strikingly captured in Maria Koijck's breast surgery photography. To reduce the environmental impact, biobased and biodegradable polymers are promising alternatives to conventional plastic medical disposables, offering sustainability while maintaining functionality. This review evaluates the suitability, circularity and benefits of various biobased and biodegradable plastics for healthcare applications and the critical role of effective waste management in enhancing sustainability in the medical sector. Implementing biobased medical plastics requires rethinking recycling strategies and waste management. Unlike fossil-based plastics, which reduce in quality while recycling, enzymatic and whole-cell biocatalytic recycling processes can preserve the quality of biobased and biodegradable materials, allowing them to be re-used for new products and offering a sustainable end-of-life solution. Integrating these materials into existing waste management requires overcoming social, economic, logistical, and technological challenges that must be addressed. Standardised regulations, awareness of the circular economy, and collaboration between academia and industry are crucial for developing medical-grade, sustainable solutions for a circular and environmentally responsible healthcare system.

Sustainability spotlight

This review critically addresses the use of biobased circular polymeric alternatives in the current health-care industry and biomedical field. The health sector, in general, places a large environmental burden on society, where reuse and recycling are often more difficult because of its more stringent regulations. However, there are options that are underdeveloped and scarcely explored. Herein, we address how conventional biomedical polymers, such as polystyrene, polypropylene and others, could potentially be replaced by polymers, such as polyhydroxyalkanoates, polylactide and other biobased. Degradation products of these fully degradable polymers can be used make new products, ultimately closing the loop. This work aligns with the United Nations Sustainable Development Goals (SDGs) 9 (industry, innovation and infrastructure) and 12 (responsible consumption and production).

1. Introduction: the plastic problem

The production of plastics is continuously increasing, driven by the growing need for these materials in our daily lives. Since their widespread adoption, which increased significantly during the second world war,[1] global plastic production reached a critical point of 400 million tonnes in 2022 (Fig. 1A) and will reach an extensive amount of 540 million tonnes by 2040.[2,3] Specifically, 50 kg of plastic is produced per person annually. The reliance of society on these fossil-based materials is a pressing and urgent issue that demands immediate attention. The environmental impact of petroleum-based plastics is concerning due to their significant contributions to pollution and health risks as these plastics are non-degradable and their production from fossil resources is energy intensive.[4] Millions of tons of plastic pollute the oceans and landfills, where they will remain for several hundred years and even release harmful chemicals.[5] Small plastic fragments have been found in the human body, including the brain,[6] as well as in crops in the form of microplastics, causing severe health problems.[7]

Highly desirable features like softness, strength, and transparency make plastic materials perfect for broad-spectrum applications[9] such as in electronics, automotive parts, packaging materials, and medical equipment. The medical sector, including hospitals, operating theatres, general practices, basic patient care, and clinical laboratories, is one of the most

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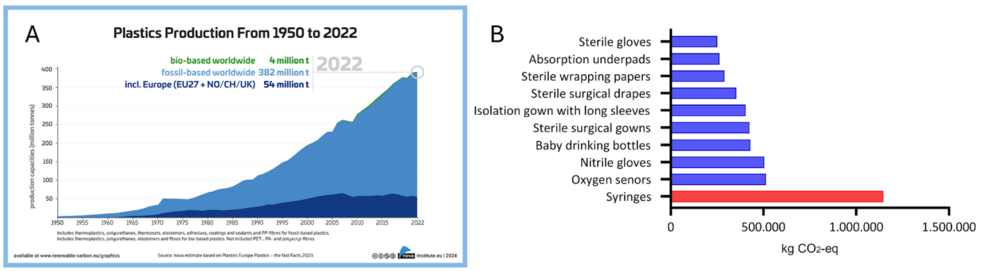


Fig. 1 (A) Worldwide plastic production from 1950 to 2022 (adapted with permission from the Nova Institute). (B) Shortlist of the medical disposables with the highest environmental impact (adapted from Project Green Deal/Duurzame Zorg, Theme 4, Nederlandse Federatie van Universitair Medische Centra, Noort *et al.*, 2024).[8]

significant industries that rely heavily on single-use plastics. This reliance is primarily due to the low-cost bulk production, cost-effectiveness and versatility of plastics, allowing their widespread use in healthcare to prevent infections and maintain hygiene.[10] Medical instruments made of steel, ceramics or glass are replaced with plastics as they can be processed in any shape and functionalized with any desired functional properties to meet the specific requirements of various applications.[10]

The healthcare and research sectors are among the most significant contributors to plastic waste. In Canada, approximately 25% to 30% of the national plastic pollution is attributed to these sectors.[11] A single hospital bed generates an average waste of 2 kg per bed per day. Among the hospital waste generated, 36% is plastic material waste, resulting in 0.72 kg of plastic waste per bed per day.[12] The environmental impacts vary between hospitals and even among departments, depending on the nature and intensity of plastic use.[13,14] Intensive care units are known as one of the most resource-intensive hospital departments. At Erasmus MC in the Netherlands, disposable gloves, medical clothing and syringes accounted for 49 900, 24 300 kg and 27 000 kg CO_2-eq., respectively.[15] Operating rooms are similarly resource-intensive, contributing to 21% to 33% of the total plastic waste, increasing to 70% when the gynaecology department is included due to its labor and delivery suites. A general audit of surgical specialties in Australia averaged 5.33 kg of waste per procedure, increasing to 10.17 kg per procedure in the United States.[14] In addition, clinical dentistry units make use of plastics for prostheses, implants, orthodontic retainers, and obviously single-use materials during treatments. Plastics are perfect to maintain our personal oral health as they are non-porous and easily cleaned, which results in a household (2 persons) creating approximately 1 kg of plastic waste annually.[16] The findings of a similar study conducted at the University of Groningen, The Netherlands, within the Faculty of Science and Engineering were equally alarming. This study reported the amount of plastic waste produced in various research laboratories, for instance, a biology laboratory with seven researchers can generate up to 4000 kg of plastic waste annually. When the plastic waste production numbers from laboratories at the university are also included, this number increases to 17 tons produced annually by a single science and engineering faculty.[17] Considering that this situation is likely similar worldwide, the gravity of the issue becomes evident.

These findings from laboratory research settings are parallel to those in clinical environments, where the extensive use of single-use medical products, such as syringes, catheters, IV tubes, surgical sheets, and sterile packaging, contributes significantly to plastic waste and associated carbon emissions. In 2022, Dutch University Medical Centers assessed the environmental impact of medical disposables based on purchasing data. An estimate of the total environmental impact of the medical disposables from six University Medical Centers participating in the study is 12 724 031.7 kg CO_2-eq. As shown in Fig. 1B, disposable syringes had the highest environmental impact (1 146 000 kg CO_2-eq.), largely due to their high plastic content of 85%,[13] followed by oxygen sensors (515 000 kg CO_2-eq.) and gloves (504 000 kg CO_2-eq.).[8] These hotspots of medical disposables highlight opportunities for circular strategies through regulatory adjustments and collaborative medical product design.[15]

Currently, fossil-based conventional plastics, which are used to make medical single-use products, account for 60% of the overall plastic demand in Europe.[3] Reduction of plastic use can be achieved by refusing unnecessary use, reusing materials, redesigning products, and advancing materials research. Replacing fossil-based, non-biodegradable materials with sustainable alternatives could significantly reduce their environmental impact, primarily when used by one of the most significant plastic users, the healthcare sector. Sustainable plastic alternatives, such as bioplastics, can possess similar characteristics as petroleum-based plastics, and therefore have the potential to replace fossil-based materials. Alternative plastics should preferably be both biodegradable, causing minimal environmental pollution, and biobased, minimising the depletion of natural resources.[18] In 2024, the market size for biopolymers was estimated to be around 18 billion USD, which is expected to reach 35 billion USD by 2030. Europe is the largest consumer in this market, holding a 43% share, and North America ranks second with a 25% share.[19] To meet the growing industrial need and replace fossil-based plastics, bioplastics need to be produced on a larger scale, and their market needs to grow. Therefore, much research is being conducted on the production and application of biodegradable bioplastics.

Addressing the pressing issue of plastic overconsumption requires a multifaceted approach, including changes in usage behaviours and transitioning to alternative materials for plastic

Table 1 Properties, applications and recycling challenges of conventional plastics used in the medical sector including LDPE, low-density polyethylene; HDPE, high-density polyethylene; and UHDPE, ultra-high-density polyethylene

Type of plastic	Characteristic properties	Application	Recyclability potential	Recyclability challenges	Reference
Polyethylene (PE)	- A wide range of properties, depending on molecular weight of LDPE, HDPE and UHDPE - Tunable mechanical strength and elasticity by controlling molecular weight	- Catheters - Single-use sanitary products	Good for HDPE and LDPE but not common for LDPE	- Difficulty in separating grades - High cost and low recycled value - Need for special equipment and high energy use	25–27
Polypropylene (PP)	- High crystallinity - Resistance to chemicals - Good mechanical properties - Easy processing	- Surgical gowns - Disposable syringes - Filters - Plastic containers	Good	- Polymer chain degradation over mechanical recycling - Loss of mechanical strength	27–30
Polystyrene (PS)	- Cost-effective - Transparency - Lightweight - High heat resistance - Moisture absorption - Brittle - Blending due to inadequate mechanical properties is favored	- Packaging - Filters - Insulators	Poor	- Difficult separation due to polymers blended with additives - High cost and low demand for recycled product - Low density and high transport costs	27 and 31–34
Polyvinyl chloride (PVC)	- Transparency - Chemical inertness - High mechanical strength - Wide range of properties - Cost-effective - Ability to adjust its rigidity by adding plasticizers	- Tubing - Catheters - IV bag packaging	Poor	- Difficult separation due to polymers blended with additives - Complex formulation - Poor thermal and photostability	10, 27 and 35

production. These steps are crucial for developing innovative recycling solutions and moving toward a fully circular process. In the healthcare sector, where plastic consumables play a significant role, changing the materials used can impact recycling and waste management strategies. This review evaluates the suitability and circularity of various biobased and biodegradable plastics for healthcare applications, focusing on their essential characteristics, potential benefits, and the critical role of effective waste management in enhancing sustainability in the medical sector.

2. Plastics in the healthcare industry

Fossil-based plastics are popular due to their diverse properties and are used in various industries, including the medical industry. These conventional plastics are versatile, durable, and have low production costs. Some of their advantageous properties, including chemical resistance, tensile strength, and resistance to stress and load before distorting, make them favourable in medical applications.[20,21] They can become soft and malleable upon heating, allowing them to be reshaped into various forms.[22] Although these plastics are petroleum-based polymers, they are compatible with biological systems without causing detrimental effects, and thus classified as conventional biocompatible plastics.[23]

2.1 Conventional plastics in healthcare

Owing to these beneficial attributes, fossil-based plastics are used as disposables and equipment in the medical field, including sutures, syringes, packaging materials, gloves, pipettes, pipette tips, tubing, plasters, and surgical gowns. The most commonly used types of plastics used in these healthcare applications include polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), and their properties, applications and recycling challenges are summarized in Table 1.[13,24]

2.2 Emerging alternatives to conventional plastics

Instead of chemical production from petroleum, most fossil-based plastics (conventional plastics, Fig. 2) can be made from renewable materials, while maintaining their properties, *e.g.* resulting in biobased PE (biobased plastics, Fig. 2). Biobased is defined in European Standard EN 16575 as 'derived from biomass'. Biomass is a material of biological origin and non-geological or fossilised material.[36] Biobased plastics are made using renewable feedstocks, such as starch, sugars, oils and other carbon-rich waste streams, which address concerns regarding resource depletion and lower greenhouse gas emissions than fossil fuel use.[37]

Biobased plastics are not necessarily biodegradable. Biodegradable materials can be broken down by microorganisms into water, naturally occurring gases such as carbon dioxide and methane, and biomass, as the microorganism population grows when they use materials as carbon sources. Biodegradability depends on the environmental conditions, such as temperature, presence of microorganisms with the proper metabolic capacities, and presence of oxygen and water. The biodegradability and degradation rate of products differ in soil, climates, seawater or fresh water, or human-like systems like industrial composting and anaerobic digestion.[36] To mitigate environmental pollution, biobased plastics must also be biodegradable, as biodegradable plastics minimize the risks of microplastics. Notably, biodegradable plastics (Fig. 3) such as polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), and polybutylene succinate (PBS) may still be derived from petrochemical sources. In contrast, biobased biodegradable plastics (Fig. 3) are made from renewable resources and fully biodegradable. The commonly used biobased biodegradable plastics

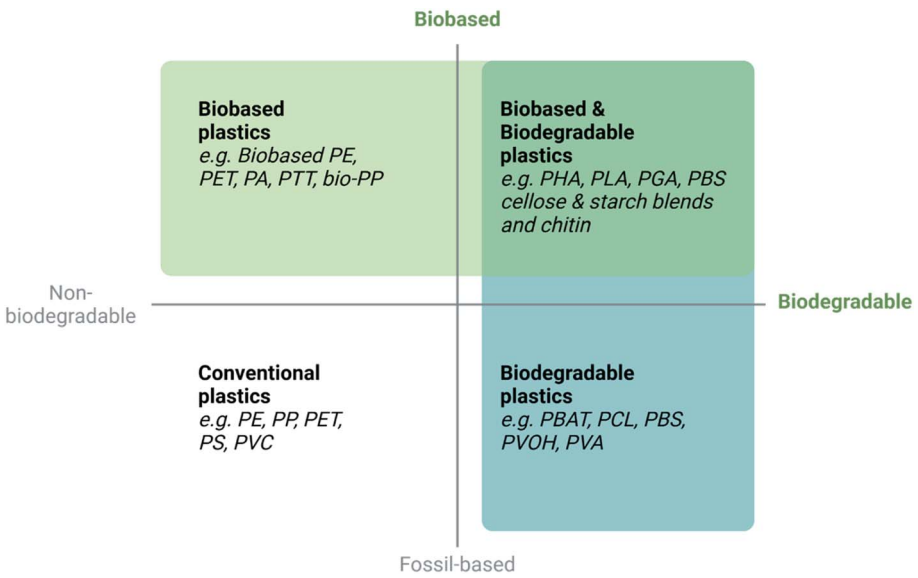


Fig. 2 Classification of different plastic polymers based on their resource and biodegradability. Green: biobased polymers produced from renewable resources. Blue: biodegradable polymers. Figure created with https://BioRender.com.

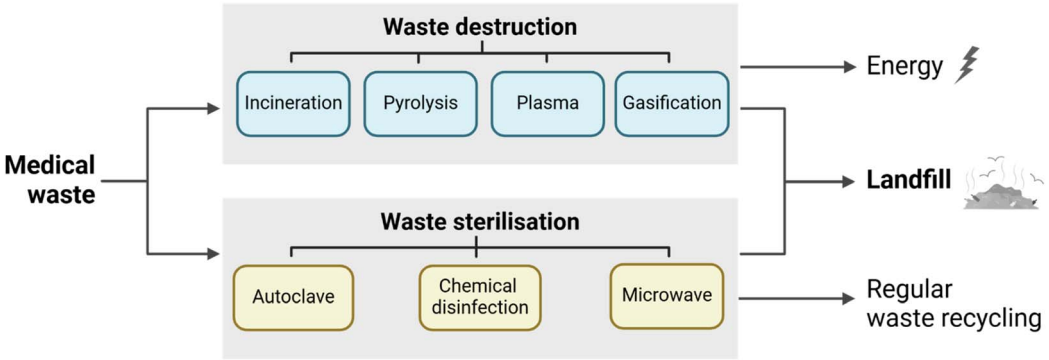


Fig. 3 Strategies for eliminating pathogenic agents in medical waste. Waste sterilisation processes are in yellow and destruction processes are in blue. Figure created with https://BioRender.com.

include starch blends, polylactic acid (PLA), polyglycolic acid (PGA) and polyhydroxyalkanoates (PHA).[37,38]

The term bioplastic can be confusing, as it describes different types of plastics with varying definitions. Bioplastics are either made from renewable resources or are fossil-based biodegradable plastic materials. Thus, to avoid confusion, both the origin (renewable or fossil-based) and the degradability of bioplastics are specified in this review.

2.3 Biodegradable and biobased plastics

Biobased plastics are being developed and introduced into medical consumer products to reduce the ecological footprint of healthcare facilities, as they are made from renewable resources.[4] Biodegradable plastics are the best option as they minimize the environmental impact by breaking down naturally and completely, reducing waste production. These materials are derived from various resources and have different characteristics, making them suitable for multiple applications. They all have unique considerations regarding their use in product development and material use. This review focuses on starch blends, cellulose blends, PLA, and PHA, among the most used and promising biomaterials.

2.3.1 Starch and cellulose-based bioplastics. Starch and cellulose-based bioplastics are derived from natural starch sources such as corn, potato, cassava, wheat, and rice waste. Starch is a carbon storage molecule, while cellulose gives structure to plant cells. However, although starch is abundant and inexpensive, its use raises concerns about competition with food production.[39] Starch consists of amylose, a chain of unbranched glucose monomers with an α-1,4-glycosidic bond and amylopectin, which has glucose branches linked by an α-1,6-glycosidic bond, whereas cellulose consists of glucose monomers linked with a β-1,4-linkage.[40]

Starch-based materials are biocompatible and have no known toxic effect on humans, making them useful for medical devices, but their applicability is limited. They have poor mechanical strength, lack thermal stability, and have inadequate physical characteristics such as high gas permeability, low melting temperature and fragile structure.[39,41] In this case, plasticisation of starch is a common way to overcome its brittleness and delicate nature, which increases its flexibility, and thus processability. Plasticisers such as glycerol and sorbitol can be added, creating a marketable form of starch-based plastics, namely thermoplastic starch (TPS).[42] TPS materials are sensitive to moisture, leading to degradation and microbial growth.[28] This indicates that starch-based materials are less suitable for consumables that must be in contact with bodily fluids such as blood, urine, and saliva but are good alternatives to packaging disposable medical items. Besides medical packaging purposes, agar-based biodegradable plastics are suitable for food packaging due to their sufficient tensile strength.[43] Other starch-based biopolymer products used as green materials in food packaging include disposable containers and cutlery.[44]

Cellulose offers better mechanical strength than starch-based materials but exhibits similar drawbacks. Cellulose and starch can be blended to improve the lower hydrophobicity, thermal properties and tensile strength of starch-based films.[45] Given that cellulose and starch only contain glucose monomers, it is impossible to change their monomer composition. The only factor that can be adjusted in starch-based materials is the number of branches. Starch and cellulose can be modified physically, chemically, and enzymatically and are often blended with other biodegradable polymers to enhance their limiting properties.[41] TPS is often blended with PLA and PCL to improve its unsatisfactory water uptake and weak mechanical characteristics.[42] However, blending can complicate recycling.[39]

2.3.2 Polylactic acid and polyglycolic acid. PLA is one of the most widely used bioplastics, which is produced from lactic acid (LA) monomer *via* chemical or fermentative synthesis. Chemical synthesis produces a racemic mixture of L- and D-lactic acid enantiomers from lactonitrile hydrolysis with strong acids,[46] while microbial fermentation can produce pure L- or D-lactic acid from carbohydrates from various crops and waste streams using natural and genetically modified microorganisms,[47] with bacterial fermentation accounting for approximately 90% of lactic acid production.[46] The polymerisation of LA into PLA depends on the LA production method and purity, affecting the molecular weight. Given that the building block of PLA is LA, no variations in monomeric composition are present apart from the enantiomer variation in PLA.[47]

The stereochemistry of the LA monomer has a direct impact on the crystallinity of the end PLA polymer. Higher percentages of L-LA (L-lactic acid) monomer make the PLLA (poly-L-lactide) polymer more crystalline. As a result of its more crystalline structure, PLLA has a more packed polymer chain, which increases its melting temperature (T_m) and glass transition temperature (T_g), as well as its degradation time. Given that T_g is a crucial factor for heat capacity, mechanical and rheological properties, all the physical characteristics of the polymer change depending on the amount of L-LA in its polymer chain.[46]

PLAs are biocompatible, non-toxic materials used for producing durable and disposable goods, fibre production, agriculture, and medical applications.[47] The broad application area of PLA also includes food packaging, while fibers are used in the textile industry to manufacture pillows, mattresses, duvets, and activewear utilizing their moisture management properties.[48] Before the '90s, PLA was restricted to medical devices due to its high production costs and restricted molecular weight. With the progress in production technologies, these issues have been solved. PLA could be produced on a larger scale with various molecular weights, making it more accessible and increasing its applicability in the medical field with time.[49] However, despite its good mechanical properties, transparency, melt-processing ability and slow degradation rate, PLA is very brittle and has low thermal stability and poor gas barrier properties, limiting its use in packaging and textiles. In the medical sector, the implementation of PLA is significantly influenced by the release and build-up of lactic acid monomer during the degradation of PLA-based medical implants, causing a decrease in the pH of the surrounding tissue, which leads to acidosis.[50] There are reported cases of mild to extreme osteolysis caused by acidosis in patients who received PLA implants such as screws, pins, and plates.[51] PLA can be blended with other polymers to overcome its limitations and poor mechanical properties, such as acidosis and inadequate tensile properties, respectively. Blending PLA with polyglycolic acid (PGA) or additives such as buffering salts results in less acidic byproducts and better hydrolytic stability of the polymer.[50] Also, the mechanical properties of PLA, such as toughness, are improved by blending it with other thick polymers and controlling its plasticisation.[47]

PGA is a highly crystalline polymer with a high melting and glass transition temperature and degrades through hydrolysis of its ester bonds, producing the non-toxic glycolic acid monomer. Its biodegradation speed depends on the size, crystallinity, length and the hydrophilic end groups of the polymer.[52] Given that PGA degrades faster than PLA due to its higher hydrophilicity, it is used for medical purposes when the material is intended to be absorbed by the human body. After degradation in the body, glycolic acid dimerizes into glycolide, which is later excreted from the kidneys.[53,54] However, PGA can be degraded by autoclaving and dry heating and should be sterilised with gamma-radiation or electron beam irradiation before use, making it less suitable for sterile laboratory practices.[52]

Alternatively, its high crystallinity, thermal stability and excellent gas barrier properties make it ideal for high-temperature and gas-sensitive uses such as packaging materials. However, despite its promising advantages, the high crystallinity, insolubility and brittleness of PGA limit its use. Therefore, PGA is often blended with PLA to form copolymers, which improves its performance and usability, creating poly(-lactic-*co*-glycolic) acid (PGLA). A copolymer consists of two or more different polymeric monomers in the same polymer chain to create a new polymer with diverse physical and chemical characteristics.[55] The crystallinity and hydrophobicity of this copolymer can be adjusted by changing the crystalline hydrophilic PGA and hydrophobic PLA ratio in the polymer chain. Therefore, the degradation speed and mechanical characteristics of the copolymer can be fine-tuned. PGLA is mainly synthesised through ring-opening of lactic acid and glycolic acid copolymerisation and is used as surgical sutures.[56]

2.3.3 Polyhydroxyalkanoates. PHAs are biocompatible, non-toxic biopolymers synthesised by bacterial fermentation. Microorganisms naturally synthesise these aliphatic polyesters in intracellular granules named carbonosomes.[57] Over 150 monomers, predominantly (*R*)-β-hydroxy fatty acids, have been identified, enabling thousands of PHA copolymer variations with different monomers, with polyhydroxybutyrate (PHB) being the most prevalent PHA.[2,57] PHAs are classified into three groups based on the chain length of their monomer including short-chain PHAs (3–5 carbon atoms), medium-chain PHAs (6–14 carbon atoms) and long-chain PHAs (15 or more carbon atoms).[42] Short-chain PHAs, such as PHB, are brittle, stiff, have high melting temperatures, lower elongation at break, and high crystallinity. In contrast, medium-chain PHAs have lower melting temperatures and are elastomeric. Therefore, a specific combination of short-chain and medium-chain monomers can alter the mechanical and thermal properties of PHAs.[58] Besides monomeric combinations of scl- and mcl-PHAs, specific added chemical functionalities and crosslinking of polymers influence their properties such as transparency, strength, flexibility, brittleness, and biodegradability.[9,59,60] The possible adjustment and versatility of the barrier and mechanical properties of PHAs allow the production of a broad range of medical products that meet strict safety and performance standards.[24,37] The adjustable characteristics of PHAs make them versatile polymers not only suitable for medical products, such as dressing materials for surgery or swabs, but also other possible applications such as pressure sensors in sound instruments and keyboards, and shock wave sensors.[61] Moreover, due to their gas-barrier properties, these polymers are suitable for applications in the food and beverage industry as packaging including disposable cups. Furthermore, the monomeric composition of the polymer is defined by the fermentation conditions, microbial strains and feedstock substrates used.[62]

PHAs are fully biodegradable under a broad spectrum of environmental conditions, with minimal effect from temperature.[39] The degradation of PHAs can take from 60 to 365 days in soil and 14–90 days in seawater, and they do not need specific industrial composting conditions such as PLA.[42] For example, a copolymer of PHB degraded by 80% after one year in the natural marine environment.[63] Biodegradability varies by the monomer composition, as PHA homopolymers (*e.g.* P3HB)

Table 2 Properties of biodegradable and biobased plastics[j]

Biodegradable biobased plastic	Primary carbon sources derived from biomass	Monomer structure	Clarity & color	Mechanical properties			Barrier properties		Thermal properties			Replacement for
				Tensile strength (MPa)	Elongation at break (%)	Young's modulus (MPa)	Water vapour transmission rate (WVTR) [g m^{-2} day^{-1}] (23 °C, 85% ΔRH)	Oxygen transmission rate (OTR)	Glass transition temperature (T_g; °C)	Melting temperature (T_m; °C)	Heat deflection temperature B (°C)	
Starch blend (TPS_{blend})	Sugar, starch	Amylose & amylopectin	Opaque, semi-transparent[f]	30.2[d]	5.8%[d]	1446[d]	70.2[d]	181–229[d]	50[d]	149[d]	47[d]	PS PP
Cellulose acetate	Sugar & cellulose	Glucose	Transparent[g]	44.2[d]	4.3%[d]	4388[d]	111.9[d]	265–308[d]	118[d]	231[d]	90.5[d]	PVC
PLA	Sugars	Lactic acid	Clear-yellow[c,e]	58[b]–74.4[d]	3–30%[c,d]	3435[d]	35.5[d]	155–180[d]	51[d]	145[b,d]	53.9[d]	HDPE[a] PP[a] PVC PS
PGA	Sugars	Glycolic acid	Transparent[h]	141.4[d]	2.5%[d]	7311[d]	1.6[d]	0.01–0.39[d]	44[d]	230[d]	199.2[d]	PE HDPE PS
PHA PHB	Sugars, fatty acids & oils	3-Hydroxybutyrate	Opaque, yellowish[i]	43.9[b]	1.6%[b]	3510[d]	5.5[d]	20–23[d]	5[d]	182[b,d]	138.4[d]	PVC[a] PP PS
PHBV	Sugars, fatty acids & oils	3-Hydroxybutyrate & 3-hydroxyvalerate	Opaque, yellowish[i]	40.2[d]	1.6%[d]	3469[d]	5.5[d]	21–23[d]	6[d]	180[d]	141.7[d]	PVC PP
PHBH	Sugars, fatty acids & oils	3-Hydroxybutyrate & 3-hydroxyhexanoate	Opaque, yellowish[i]	19.8–31.3[d]	12–15%[d]	796–1546[d]	7.9–11.6[d]	59–127[d]	1–3[d]	121–158[d]	65.8–97.5[d]	PVC LDPE/HDPE

[a] Ref. 24. [b] Ref. 72. [c] Ref. 73. [d] Ref. 74. [e] Ref. 75. [f] Ref. 42. [g] Ref. 76. [h] Ref. 77. [i] Ref. 78. [j] Property values may vary depending on the measurement methodologies as well as the standards and testing conditions applied. They should not be considered absolute benchmarks.

generally have a lower degradation rate than copolymers such as PHBV.[64] Thereby, PHAs can fully biodegrade as the polymers break down into CO_2 and H_2O under aerobic conditions or methane under anaerobic conditions.[57] Microbes grow because they use PHA as a carbon source, and also microbiological cellular waste forms. In a controlled environment, the degradation of PHA waste plastic is a potential fermentable renewable feedstock for the production of PHA materials.[65,66]

The main drawback of PHAs is their high production cost, which is driven by their energy-intensive, environmentally unfriendly downstream processing. PHA extraction requires breaking cells and purifying the polymer by removing the residual biomass, chemicals and waste.[67] Advances in eco-friendly extraction methods, such as enzymatic treatments,[2] autolytic microbial strains, phages,[68] and supercritical fluids,[69] aim to lower costs and improve sustainable scalability.

Although PLA- and starch-based bioplastics are very useful due to their advantages such as low cost and high availability,[38] their limitations of specific biodegradation conditions and poor mechanical properties, such as brittleness and low thermal stability, can only be overcome by blending them with other materials. PHA copolymers are a more reliable and sustainable option for medical applications, ensuring environmental and health safety.

2.4 From conventional plastics to biodegradable and biobased plastics

Different applications require plastic materials with specific characteristics, including a wide range of characteristics such as mechanical properties, which determine how a material responds to physical stress such as stretching and bending; barrier properties, referring to the ability of materials to restrict the passage of water and gases through their structure; thermal properties, which are necessary to understand how materials behave during heat-based processes such as sterilisation and processing; and optical properties such as clarity, and color, affecting the application materials are used in, such as clear packaging.[70,71] Understanding these characteristics is crucial in evaluating the suitability of biobased plastics for replacing conventional plastic materials, where their material properties must align with the requirements of fossil-based plastics. Table 2 provides the general specifications of biobased biodegradable plastics. As shown, starch-based bioplastic TPS, cellulose acetate, PLA, PGA, and PHA exhibit unique characteristics that vary significantly, influencing their functionality as replacements for conventional plastics in the medical field.

Packaging is a major contributor to plastic waste in hospitals, including blister packs, sterile wrappers and containers made from PS and PE, which require strong barrier properties. Barrier properties refer to the ability of materials to restrict the passage of water and gases through their structure. Controlling the barrier and exchange of gases helps to preserve quality and functionality.[79] Environmental conditions significantly influence the barrier properties of materials. Therefore, oxygen tests need to be performed in different relative humidities. Starch blends and cellulose-based materials have a higher water vapour and oxygen transmission rate than other bioplastic materials. This increases their moisture sensitivity, which could lead to a reduction in mechanical strength and changes in material properties, limiting their use in humid environments and extended storage.[80] Their oxygen transmission rate (OTR) is higher than that of PHB, PHBV and PGA, making PLA and PHBH better replacement packaging materials, such as packaging made of HDPE. For the identification of products, the packaging needs to be transparent. In this case, PLA and PHA can have a yellowish color, and thus transparent materials such as cellulose and PGA would function better in this application. Additionally, PHAs have a high HDT, suggesting their strong potential for packaging and equipment requiring heat-based sterilization. Nowadays, PHAs are used for the production of diapers, bottles[39] and cups by the company Happy Cups (The Netherlands). These cups show the potential use of PHAs as drinking cups, medicine cups or packages. Cups are moulded, but the application of PHAs can be broadened due to 3D-printed filaments.[81] The global PHA organisation GO!PHA shows the applications of films, containers and bags produced by various companies.[82]

Catheters can be made out of PVC, a flexible, bendable material. Thus, owing to their enhanced flexibility, adjustable PHAs and PLAs are good alternatives to PVC, especially given that PVC is used in rigid forms too, *e.g.* protective gear. However, PLA might need some plasticizers to adjust its mechanical properties. Thereby, catheters must not leak or break under particular pressure, making bioplastics with higher tensile strength, such as PGA, of particular interest to ensure safety and durability.[83] PHBH exhibits a much lower tensile strength, which makes it better to replace products where elasticity and softness are more important than tensile strength, such as gloves. Labware and syringes can be made out of PP. PP is a stiffer material that could be replaced by PLA based on the mechanical properties such as tensile strength and elongation at break of the latter. PHB and PHBV are more brittle than PP. However, if PP products need to be more flexible, such as IV bags, protective gear and tubing, their flexibility can be tweaked based on the percentage content of 3HV of PHBV. PLA has a Young's modulus close to that of PHB and PHBV, which is higher than that of PHBH but lower than that of PGA. PS is used in labware and packaging as well. The rigid versions of PS can also be replaced by PHB and PLA based on their mechanical properties. PLA performs adequately in moderate processing environments, though it may not be ideal for equipment requiring frequent sterilisation as it has a lower HDT.

Determining the thermal properties of materials, such as their melting and glass transition temperatures, is necessary to understand how they behave during heat-based processes such as sterilisation and manufacturing with melt electro-writing and injection moulding.[74] In general, equipment requiring frequent sterilization needs to have higher thermal stability. The heat deflection temperature (HDT) is when a polymer begins to deform under a specified load. It is a key property used to assess the thermal stability of materials, and consequently their resistance to sterilization conditions.[84] A higher HDT means that the polymer can resist higher temperatures during sterilization. PHA and cellulose acetate have a higher HDT than

other biobased polymer materials, which makes them more suitable options for manufacturing equipment that needs to be sterilised by heat.

Replacing traditional plastics with biodegradable, biobased alternatives depends mainly on the specific application and intended use of the product. Ultimately, the choice of bioplastic must balance factors such as mechanical strength, biodegradability, cost, and environmental impact, ensuring that the material meets the functional requirements of the product, while being sustainable.

3. From recycling to circular

Hospitals, healthcare facilities and laboratories for clinical research generate enormous plastic waste due to the need for sterile and disposable medical products. Consumer products, mostly made from conventional plastics, pose environmental challenges in hospital environments, particularly waste management and recycling.[85] Additionally, a significant portion of this waste is classified as contaminated, meaning it has come into contact with human bodily fluids, pathogenic sources, or other possibly hazardous biological materials. Consequently, it poses a potential risk of infection or disease transmission when not properly disinfected, effectively disabling reduce, reuse and repair options. Given that this polymeric waste varies in terms of type, composition, properties, and other factors, it is essential to separate them before recycling. Manual sorting, flotation, and X-ray sorting are examples of waste separation methods. Each group of sorted waste can then undergo the appropriate recycling method for its category. This approach enhances both the efficiency and quality of the final recycled product.[86,87]

3.1 General plastic recycling practices

Material recycling can occur through physical, chemical, mechanical, biological or energy recovery methods based on type, composition and properties. Mechanical recycling is one of the most widely used methods. Firstly, plastic waste is cleaned and ground into smaller particles. The ground material is then melted using an extruder and reformed in further processes such as moulding. Unfortunately, due to the high shear rates and temperatures, there is a significant decline in the quality of most of the properties of materials in this method.[88] In the chemical recycling process, the polymer material is broken down into its original monomers and reused in polymerisation. The depolymerisation of polymer waste can be achieved using special solvents, such as toluene, xylene, and tetrachloroethylene, or high-temperature degradation, either in the presence or absence of oxygen.[88–91] As a result, the polymer material is broken down into its original monomers and reused in polymerisation. However, the use of special solvents, need for complex recycling units, and high energy consumption are significant drawbacks of this method.[92] Finally, energy recovery methods are employed when plastic waste is no longer suitable for recycling. This process involves incineration to generate heat and electricity at the cost of greenhouse gas emissions. At this stage, plastic waste reaches the end of its life, as it is no longer part of a circular economy.[63] Table 3 provides an overview of these three recycling methods.

3.2 Hurdles in medical plastic waste recycling

In the context of medical plastics, their recycling is more complex. The potential contamination of hospital waste with various viruses, bacteria, blood or other body fluids poses challenges for recycling processes, prioritising incineration or landfill.[10] Regulations are needed to ensure patient safety, minimise infection risks, and maintain hygiene.[94] Firstly, accurately and correctly separating the waste is necessary as medical devices and packaging frequently combine different plastics and other materials. Medical staff must be trained to separate plastics and other materials such as metals correctly.[10]

Table 3 Advantages and disadvantages of different methods for recycling plastics

Recycling method	Operational steps	Advantages	Disadvantages	Reference
Mechanical recycling	Recycling polymers by: - Grounding - Melting with an extruder - Compounding and moulding	- Cost-effective - Simple and widely used	- Quality reduction - Not suitable for all polymers	88
Chemical recycling	Depolymerisation of polymers with:	- High-quality material production	- High energy consumption	92
	- Chemical solvents	- Can handle contaminated and mixed waste	- Requires complex and expensive facilities	
	- High-temperature degradation (in the presence or absence of oxygen)	- Suitable for a wide range of polymers	- Environmental risks due to solvents	
Energy recovery	Incineration of plastic waste to produce heat and energy before landfilling	- Non-recyclable plastic waste goes to valuable energy	- Emissions and air pollution	63 and 93
		- Reduces the waste volume for landfills	- No plastic elimination, but reduction - Not a part of a circular economy	

For a used hospital product to enter the normal recycling cycle or landfill, it is essential to ensure it is entirely free of any risks or contamination. Various methods can be used to eliminate pathogens depending on the type of waste and contamination. Processes to eliminate contamination can be divided into two categories, waste destruction and waste sterilisation processes, as illustrated in Fig. 3 (ref. 95).

Waste destruction processes occur at higher temperatures, leading to material breakdown. This category includes processes such as incineration, pyrolysis, gasification and plasma.[95] Unfortunately, using the waste as feedstock in recycling units is impossible, and the destroyed waste ends up in landfills. However, waste destruction processes can also be used to generate energy. Table 4 details various destruction methods.[96]

In contrast, waste sterilisation processes are carried out at lower temperatures using autoclaves, microwaves, and chemical disinfection. Sometimes, the hospital waste output from these processes can be used as raw materials in general recycling units. Table 5 provides more detail about sterilisation methods.[96]

By reviewing the above-mentioned content, it is clear that managing hospital waste involves many additional challenges in sterilising it before recycling. One of the reasons why hospital waste recycling is not widely accepted in many regions is the difficulty in dealing with these challenges. In many countries, there is insufficient management for segregating hospital waste at the source, and sterilising all of this waste requires a significant budget. As a result, the cost of recycling medical waste becomes relatively high, and thus governments to prefer to minimise costs through landfill disposal or incineration. However, this approach has a significant environmental impact as it releases greenhouse gases and harmful pollutants into the atmosphere and generates high energy demand. Incineration of one-time-use plastics breaks the recycling loop and makes it impossible to recover resources, perpetuating a linear economy.[105] This limitation highlights the need for alternative recycling solutions that align with circular economy principles.

3.3 Biobased and biodegradable plastics as a circular solution for medical waste

Using biobased and biodegradable plastics instead of fossil non-biodegradable plastics in the medical industry could lower the impact of the medical sector on plastic consumption as it is a solution to prevent the incineration of plastic waste. In addition to mechanical and chemical methods for the recycling of fossil-based plastics, these biodegradable materials can be recycled through anaerobic digestion, composting or enzymatic methods, providing new end-of-life options and potential for circularity.[9,63] Fig. 4 shows an overview of the classical and new recycling procedures related to biodegradable plastic waste. As indicated, mechanical recycling and cleaning waste will decrease the quality of the plastic, often leading to the downcycling of materials into lower-value products and requiring the addition of new virgin material to preserve the quality of the mechanically recycled material.[106] In contrast, employing specialized microorganisms, enzymes, or a combination of both, biodegradable polymer waste can be specifically depolymerised into building blocks for new products, so-called carbon-rich feedstock.[107] The degradation products, which are all carbon molecules, can be used in microbial fermentation to make new materials. In this way, the quality of the plastic will be preserved, which is a significant advantage of biodegradation and enzymatic recycling. In biodegradation, polymers degrade

Table 4 Processes for medical waste destruction, their operational conditions, advantages and disadvantages

Destruction process	Operational conditions	Advantages	Disadvantages	Reference
Incineration	800–1200 °C with oxygen	- Suitable for all types of hospital wastes - Serious reduction in waste volume - Sterilized waste - Energy recovery	- Release of carbon dioxide, ashes, and other dioxins - Contributes to air pollution and greenhouse effect - Expensive	95 and 97
Pyrolysis	540–1000 °C without oxygen	- Suitable for a wide range of hospital waste - Reduce waste volume	- Release of nitric oxide, carbon monoxide, and sulfuric dioxide - Contributes to air pollution and greenhouse effect - High operation costs	98 and 99
Plasma	Over 3000 °C	- Destruction of pathogens or hazardous agents remain - Energy recovery	- High operation cost - Require technical personnel to operate the system	97 and 100
Gasification	900–1100 °C with a small amount of oxygen	- Energy recovery - Prevents the formation of dangerous nitrogenous, halogenated and sulfur compound	- More energy requirement for waste with high percentages of humidity	95, 97 and 101

Table 5 Processes for medical waste sterilisation, their operational conditions, advantages and disadvantages

Sterilisation process	Operational conditions	Advantages	Disadvantages	Reference
Autoclaves	120–130 °C with pressure and steam	- Simple operational technology - In use for many years - Sterilization of the waste - Low costs	- No reduction in waste volume - Need for extra shredding for volume reduction - Need for extra drying - Not suitable for all types of wastes	97 and 98
Chemical disinfection	Combining waste with chlorine-based & non-chlorine-based chemicals	- Controlled process - Different processes for different types and levels of waste	- High operation cost - Environmental issues caused by the use of chemicals	102 and 103
Microwaves	- Uses high intensity of radiation and moisture inside the waste	- Simple technology - Low energy consumption - Minimal emission	- Not suitable for all types of wastes - High operation costs	104

under aerobic or anaerobic conditions using microorganisms as whole-cell catalysts. Under aerobic conditions, *e.g.* in soil and marine, biodegradable polymer waste degrades into CO_2 and H_2O.[108] Leftover compost can be used in the agricultural industry as nutrition for soil.[9]

Biodegradation in at-home and industrial composting still has a linear life cycle as it threatens plastics such as single-use plastics, as compost is an only product and the polymer is not recycled into new products.[109] Valuable intermediates must be extracted as much as possible to maximise the benefits of composting. Anaerobic biodegradation, including classic composting, occurs when the polymer degrades without oxygen, also called anaerobic digestion, which can extract valuable intermediates in controlled environments. This process generally occurs in four stages, as presented in Fig. 5. The first stage is hydrolysis, where bacteria release enzymes, such as depolymerases, to break down complex biological macromolecules such as proteins, lipids and carbohydrates into monomers and oligomers of amino acids, fatty acids, and sugars. During this fragmentation, the polymer is cleaved into a more straightforward form before it is further degraded and assimilated by microorganisms.[110] The second step is acidogenesis, which is the absorption and conversion of these products into intermediates such as volatile fatty acids (VFAs) *via* acidogenic microorganisms.[63,111] In the third stage, acetogenesis, the conversion of intermediates to acetic acid, hydrogen and carbon dioxide occurs. In the final methanogenesis step, methanogenic organisms use the intermediates to produce methanol for energy recovery.[63,111] The produced carbon-rich intermediates, such as VFAs, alcohols, and carbon dioxide, are used as feedstock for producing PHAs, highlighting the circularity of biodegradable polymers, using biodegradation as a functional property.[62,112] However, due to contamination risks in medical waste, disinfection processes must be performed, which could affect their biodegradation. Hereafter, leftover unprofitable compost must be checked for any toxic products, or it needs to go to incineration to reduce the risks of widespread pathogens.

The speed of the biodegradation of biodegradable plastics depends on various physical and chemical factors such as the molecular weight, crystallinity, and presence of impurities and

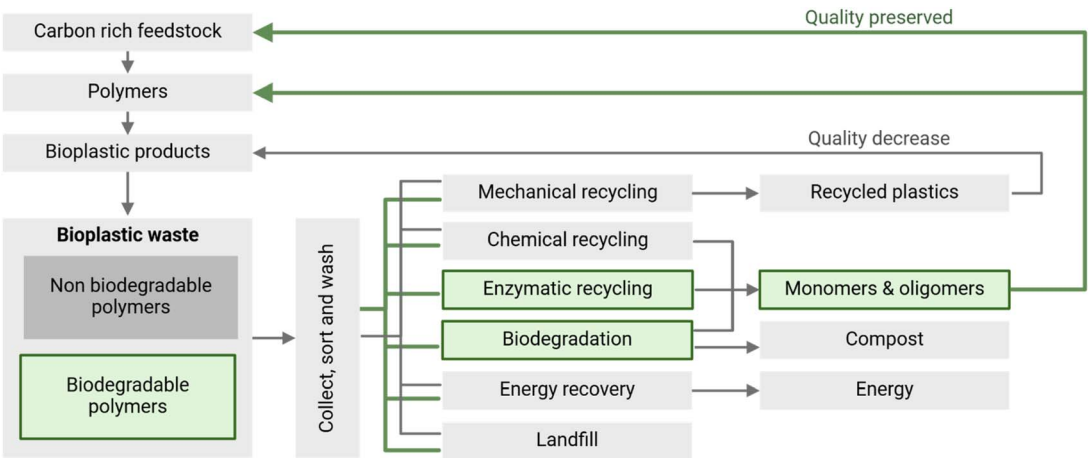


Fig. 4 Bioplastic recycling methods. Green: recycling of biodegradable bioplastics with a preserved quality. Figure created with https://BioRender.com.

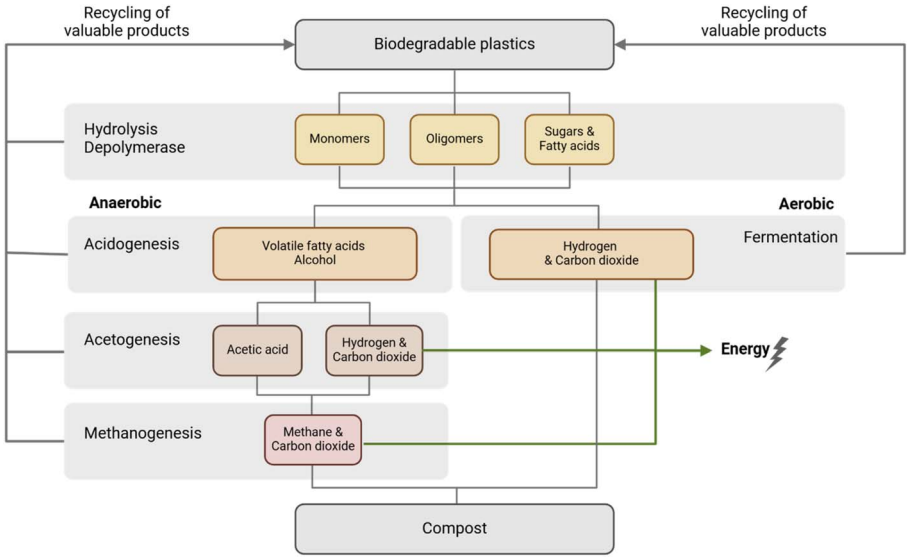


Fig. 5 General steps of biodegradation as a recycling process and generated valuable products. Colours show valuable products of a circular economy, while compost is a linear life cycle product. Created with https://Biorender.com.

additives in the polymer, and environmental conditions such as temperature, pH, humidity, and oxygen levels. Studies on semi-crystalline polymers indicate that microbes first target the more flexible amorphous regions of the polymer during degradation, and then attack the crystalline regions.[113] Amorphous regions allow the permeation of moisture and microorganisms, increasing the available surface area.[110] Based on this process, it can be stated that polymers with high crystallinity, such as PLLA, undergo degradation much more slowly than other polymers with lower crystallinity.[114] This shows that the degradability of biodegradable plastics differs under different conditions and the needed microbial community composition and is highly influenced by the material itself. A broad range of conditions is needed to fully convert a mix of biodegradable plastic waste into monomers and oligomers by these whole-cell biocatalysts.[115] However, biodegradation can extract the chemical potential of polymers by creating specific product streams that can be upcycled and recycled. This feature is especially desirable in plastic products of different polymers, such as layered plastics and textiles.[107] In the case of polymer waste with both biodegradable and non-biodegradable polymers, degradation will continue until the non-biodegradable polymer comes into contact with the degrading enzyme or microorganism.[113] Hereafter, materials could be used in other standard recycling methods. This shows that even waste streams with partially biodegradable plastic materials can be recycled. However, blending biodegradable and non-biodegradable polymers complicates their recycling.[116]

Instead of using specific conditions with microorganisms to depolymerise plastic materials, specialised enzymes can be used. Enzymatic degradation offers a more circular life cycle than using whole-cell catalysts as a recycling method. The monomers of plastics are fully recovered and not used as an energy source for microorganisms to grow. Thereby, this method generates no compost as a product.[107] Unlike conventional plastics, the monomers and oligomers of degraded biobased and biodegradable plastics can re-enter the production cycle as virgin carbon-rich feedstock after proper treatment. Given that enzymatical biodegradation is a very attractive method for the biodegradation of plastic waste, advanced techniques for enzyme discovery are reviewed even to degrade conventional plastics such as PE and PS.[117] However, regarding sustainability, plastics must be from a biobased or renewable origin.

Cellulose-based plastics, such as cellulose acetate, are degraded through microbial esterases that cleave the acetate groups of polymers. Cellulases can further hydrolyse the remaining backbone, resulting in glucose monomers.[118] Starch-based materials follow a similar pathway, where amylolytic enzymes such as alpha-amylase break down starch into glucose monomers.[119] In microbial biodegradation, glucose is directly used as the carbon source, limiting microbial degradation as a recycling method. However, monomers can be repurposed in cell-free enzymatic degradation. The obtained glucose can even be used for bioethanol production[120] or as a carbon source for new microbial fermentation, enabling a closed-loop system.[121]

Currently, PLA is only degraded under industrial aerobic composting settings at high temperatures of 50 °C to 70 °C with high humidity and the presence of microbial activity, as residential composting takes up to 60 days.[122,123] Using purified enzymes and specialised microbes speeds up the biodegradation process. Essential enzymes in PLA degradation are proteases (serine proteases), lipases (esterase) and cutinases, as they process PLA into its constituent monomer, lactic acid and oligomers of lactic acid. Proteinase K is one of the most captivating enzymes in the biodegradation of PLA.[124] After isolating these proteins in high concentrations, the maximum capacities of these enzymes depend on the environmental conditions and polymer properties.[125]

PHAs are another type of polymer that can completely decompose in various environments, such as soil and fresh water lakes. Similar to all biobased polymers, the degradation of PHAs can occur in aerobic and anaerobic environments,[126] resulting in different degradation products. The degradation of PHAs is catalysed by two main enzymes, PHA hydrolase (PhaY) or PHA depolymerase (PhaZ).[57] The enzyme hydrolyses PHAs into water-soluble intermediates, which can be used as carbon and energy for growth.[127] Various factors influence the activity of the enzyme, including chemical composition and complexity, which are influenced by the monomeric composition.[57] PHA depolymerase can be produced intracellularly and extracellularly. The intracellular enzymes depolymerize the polymer when needed for the metabolism of the bacteria in harsh environments. Extracellular depolymerase can depolymerize materials in the environment into monomers, which can be recycled into new products.[128]

Reusing monomers such as glucose, lactic acid, and 3-hydroxy alkanoates reduces the demand for feedstock for plastic production. This approach supports a circular economy as plastic waste is transformed into valuable feedstock to make new biomaterials, biofuels and specialised chemicals. Furthermore, as medically contaminated materials are entirely fragmented and processed by microorganisms to create new materials, this may even present new opportunities for regulatory routes regarding safety. Implementing biobased and biodegradable plastics in major plastic industries could significantly reduce greenhouse emissions, while contributing to the circular economy and sustainability.

4. Rethinking waste management: challenges in recycling biobased biodegradable clinical waste

As stated before, the current approach for waste management by the healthcare sector relies on incineration. However, although this is highly effective in limiting biological hazards, it results in the loss of valuable resources, and it does not align with circularity principles, such as resource recovery, material use and waste minimisation. This reliance is recognised as unsustainable, and transitioning to a sustainable future requires an evolved sustainable waste management system. The current approach is a segregation strategy, where reusable plastics must be separated from contaminated waste streams before incineration or landfilling. Various types of waste are divided into different containers as a first step of waste management. Consequently, uncontaminated materials can be reused or recycled classically whenever possible.[129] However, the ultimate goal is to create a circular biobased system where all plastic from the healthcare sector is recycled. In this vision, biobased and biodegradable materials must be cleaned, correctly separated, and processed for circular recycling, keeping the materials within the loop. To achieve this, society must rethink the waste management system to prioritise circularity, while addressing contamination risks differently.

Although shifting to biobased and biodegradable materials is promising, handling waste materials presents significant challenges. The key issue is raising social awareness. Additionally, regulatory, infrastructure, and technological hurdles must be addressed alongside cost considerations. Various initiatives have been launched to tackle these challenges and integrate biobased and biodegradable materials as a sustainable alternative.

4.1 Navigating through regulations and legislation

The circular economy and waste management have become priority topics for authorities and global organizations, especially in the healthcare industry, one of the most significant contributors to plastic waste creation. To achieve this, policymakers in each country work on aligning developments with related regulations to help implement a better circular system. One of the ways of implementing this idea is the reuse principle. Reusing single-use medical equipment has been accepted by following strictly regulated rules in some countries such as the USA and Germany. However, this is still not a system accepted and practised by the majority.[130]

Although many countries mandate the incineration or sterilization of medical waste, regardless of its recyclability, to prevent health risks, this approach presents challenges due to inconsistent decisions on managing medical plastic waste specifically. This inconsistency results in a lack of universally standardized guidelines for disposing of or sterilizing medical plastic waste for reuse. Thus, to ensure the safe practice of reuse principles, it is crucial to critically evaluate the requirements, including preliminary risk assessments, regulations, and certifications during production and the validation of reprocessing single-use medical plastics.[131]

Currently, no rules and regulations exist for designing recyclable biobased polymer products. However, new initiatives have been started to tackle this problem and be ready when the time comes for biobased polymers to take their place on the stage as a greener replacement for petroleum-based polymers. One of these initiatives is ReBioCycle, an action that is funded by the Circular Bio-based Joint Undertaking (CBE JU) that funds the biobased, sustainable industry in Europe.[132] This initiative aims to approach the current usage and recycling challenges of biobased polymers by working on creating a sorting system for mixed biobased plastics, upscaling new recycling technologies, including mechanical, chemical, and enzymatic, integration of these developed recycling systems into real waste management plants, focusing on the same grade of recycled polymer as the virgin product, and creating assessment methods for all these planed points according to the safe and sustainable by design (SSbD) approved the European Commission in the next 4 years.[133]

4.2 Costs of bioplastics and the economic feasibility

To shift to a biobased and biodegradable plastic world, these plastics need to compete with fossil-based conventional plastics, which have low production costs, bulk manufacturing and are compatible with known infrastructures in production,

sorting, recycling and end-of-life remediation.[39] Conventional plastics benefit from years of optimisation, whereas biodegradable bioplastics are still under development. This maturity gap contributes to the higher costs of bioplastics, ranging from two to ten times the price of conventional plastics.[134] Developing biodegradable alternatives for medical equipment is a cost-prohibitive process, especially during research and development.[135] Cost-efficient bioplastic production relies on the availability of biobased feedstocks, advances in fermentation processes, specialised production strains and efficient downstream processing to improve yield and affordability. Additionally, recycling and composting remain more expensive than incineration methods.[134]

According to a recent report from European Bioplastics, an organisation representing the bioplastics industry in Europe, the global production capacity of bioplastics, both biodegradable and non-biodegradable, was approximately 2.18 million tons in 2023. This capacity is expected to grow to around 7.43 million tons by 2028 (Fig. 6A (ref. 136)). The market adoption of biodegradable bioplastics remains low, accounting for only about 0.2% of the total global plastic production capacity in 2023, with PLA dominating the segement at 75% of the biodegradable bioplastic production.[134] Based on the total production data from EUBP, the global production volumes of various bioplastics can be listed and measured in tonnes per year. In 2023, 866 000 tonnes of biodegradable bioplastics were produced, as indicated in Fig. 6B.

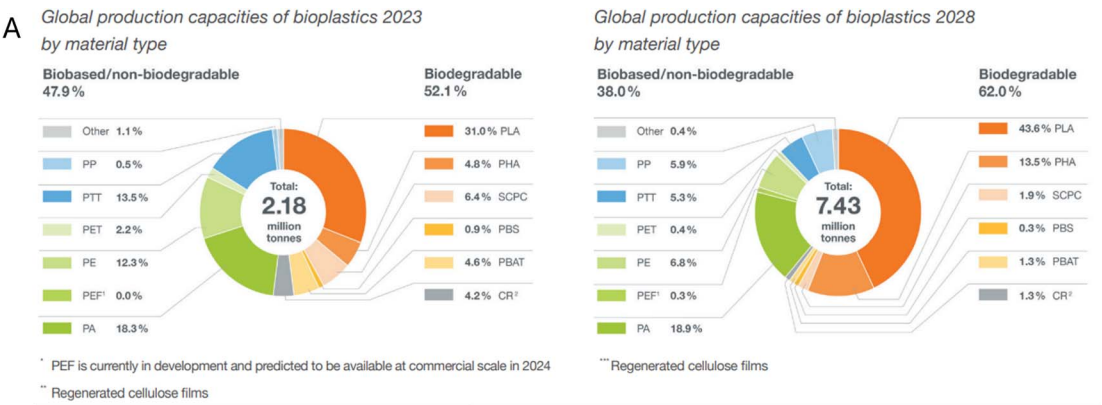
The amount of plastic waste generated in a single hospital is considerably higher than the current production levels of biodegradable bioplastics. The UMCG has approximately 1300 beds, with 0.72 kg of plastic waste per bed per day (ref. 12) resulting in 341.640 kg of plastic waste per year in only one academic hospital centre, leaving out all laboratory research performed. Considering the total production of biodegradable bioplastics in 2023 of 866 000, the production of biodegradable plastics must increase significantly to meet the growing demand for plastic materials in medical and laboratory applications.

4.3 Technological and logistic barriers

4.3.1 Contamination from chemical and biological hazards. Chemical additives are carefully selected to enhance specific properties of plastic materials, improving their processability and flexibility for desired applications. For instance, incorporating compatibilizers such as maleic acid can enhance the durability and strength of bioplastics such as PLA, while adding glycerol and palm oil increases their flexibility.[137] However, these additives introduce challenges regarding their end-of-life processing. Ongoing material research aims to eliminate harmful additives, such as endocrine-disrupting chemicals (EDCs) such as phthalates and bisphenols, which can leach into the human body and cause severe health effects.[106] Moreover, colours and pigments also impact the recyclability of plastics, further complicating waste management.[10]

In addition to chemical additives, other hazardous substances, such as disinfectants, laboratory reagents, and pharmaceuticals (*e.g.* antibiotics and cancer treatments), complicate recycling processes and affect the quality and safety of recycled plastics. In Finland, the plastic packaging of medicines must be rinsed before being sorted into plastic waste collection. However, this practice leads to increasing concentrations of pharmaceuticals in wastewater treatment plants, ultimately leading to environmental contamination.[138]

A



B

	Global production (tonnes)	
Biodegradable bioplastic	**2023**	**Forecast 2028**
Regenerated cellulose films (CR)	90 000	96 000
PLA	676 000	3 240 000
PHA	100 000	1 000 000
Total	866 000	4 336 000

Fig. 6 Global production of bioplastics in 2023 and the forecast for 2028. (A) Production capacities in percentage, reproduced with permission from European Bioplastics (EUBP). (B) Production capacities in tonnes calculated as a percentage of the total production capacities listed by the EUBP.[136]

Medical disposables have additional challenges, as they often come into contact with biological fluids. The plastic disposables are labelled as possible contaminated waste, carrying infection risks for humans. Without proper sterilisation, recycling can lead to cross-contamination and public health hazards. Therefore, reuse after sterilisation, whenever possible should be prioritised, and governmental policies should promote this. When reusing is not feasible, the recycling industry must take responsibility for collecting, sorting and processing these materials. However, due to economic concerns and infection risks, the recycling industry remains hesitant to dispose of medical waste. Standard operating procedures and disinfection regulations must be implemented to ensure the safety of people and mitigate risks.[10]

4.3.2 Efficient sorting for effective waste management. With biobased biodegradable materials replacing conventional plastics, proper medical waste segregation remains a significant obstacle in waste management. A waste audit in the OLVG hospital in The Netherlands has shown that waste could be composed of 15 types of different plastics.[106] This mixture undermines the efficiency of recycling and composting systems. In many healthcare settings, biodegradable and non-biodegradable waste is mixed due to inadequate separation or insufficient training among staff. However, shifting to a workflow where biodegradable bioplastics are separated at the source is logistically very complex and would require major changes in clinics and hospitals. This so-called manual sorting is highly labour-intensive and relies on sorting based on shape, color, type or composition, which is important for the good recycling of biodegradable biobased plastics.[10] However, many biobased and biodegradable plastics have visual similarity with other conventional plastics. Clear labeling placed at the product is important for the consumer to inform about specific properties and the correct disposal methods of the plastics.

To realise high-quality recycling, efficient and correct sorting is essential, as the aim is to obtain high-purity streams to produce high-quality recyclates. Biobased plastics often closely resemble conventional plastics in color and shape, but advanced sorting technologies, such as density separation and near-infrared (NIR) sorting methods and hyperspectral imaging, can distinguish biodegradable materials from conventional plastics as long as the spectral libraries of these plastics can be used as a reference.[139] Recently, various studies have been conducted, such as using innovative and AI-based waste segregation systems to address this challenge.[140,141] The National Test Centre for Circular Plastics in The Netherlands is an example of a knowledge hub linking AI-based decision models combined with NIR detection, hyperspectral imaging and density-based separation modules, with waste processors and policy developers. The data generated in these pilots are translated into practical recommendations for material design, labeling standards and infrastructure adaptations.[142] Other initiatives, such as digital watermarks and codes on packaging that can be detected by high-resolution cameras, are being researched for the separation of packaging material.[143] However, further development and research are needed to achieve this goal as digital watermarks are perhaps not suitable for all products and the separation and recycling of biobased plastics such as PLA from waste streams with conventional plastics is still affected by pollution of the waste stream, and the sorting yield with NIR is below 90%.[144]

4.3.3 Challenges in degradation and breakdown. Recycling biodegradable waste requires specific conditions that are not universally available. Each biodegradable polymer introduced in this review requires specific enzymes or microorganisms for its biological degradation, which may not be effective on other polymers. Therefore, to establish an industrial cycling unit, it is essential to have an advanced separation unit or to create conditions that allow the simultaneous use of multiple enzymes. Additionally, as another example, the volume: surface ratio of biopolymers directly affects their degradation rate. Smaller pieces degrade more quickly. As a result, a variation in size leads to differences in the degradation rate of biopolymers, making the process design more challenging. Temperature is also an essential factor in biodegradability. As another example, polymers such as PLA only degrade well above their glass transition temperature. Given that different grades of PLA are found in polymer waste, which may even be mixed with other polymers, determining a specific temperature for the biodegradation of all waste is a challenging task.[145] Therefore, industrial composting processes become complicated. Inconsistent degradation can lead to residues in composting facilities, reducing the overall efficiency of waste treatment, which still needs further attention and solutions.

Another critical factor to consider when designing a recycling unit is the potential formation of microplastics during the degradation process. When polymers break down, there is a possibility of forming small fragments of these materials, each less than 5 mm in size, which are known as microplastics.[146] The formation of microplastics happens in both biodegradable and non-biodegradable polymers. While the initial stages of bioplastic breakdown can happen quickly, the process slows significantly once they turn into microplastics. This is a significant environmental problem because microplastics can harm all living creatures.[72] Research has shown that the lifespan of microplastics generated from bioplastics is much shorter than microplastics derived from conventional plastics. For example, microplastics from PET can remain in the environment for hundreds of years, microplastics from PLA will break down within a few years, and microplastics from PHA will decompose within a few days to a few weeks. A shorter microplastic phase limits hazardous consequences to natural environments on microbes, animals, plants and humans. However, it is still necessary to further investigate the risks posed by these microorganisms and propose ways to minimize the production of this category of materials in cycling units.[126]

5. Conclusion: closing the loop with biodegradable bioplastics

The widespread use of plastics in the medical sector has significantly increased plastic consumption and waste generation. Although these materials offer essential benefits such as

easy processing, cost-effectiveness and versatility, their fossil-based origins contribute to environmental challenges. As a major consumer of plastics, the healthcare industry plays a crucial role in this issue. The transition to biobased biodegradable polymers presents a promising solution, reducing the reliance on fossil fuels, while offering a novel, circular way of disposal that mitigates plastic waste. Enzymatic recycling uses whole-cell biocatalysts or enzymes to depolymerize biodegradable polymer waste into building blocks, which can be used to produce new products. This process creates a closed-loop manufacturing system, preserving the quality of the plastic. This transition will provide a sustainable end-life for plastics, minimize environmental impact, and help to build a circular economy.

Although replacing conventional plastics with biobased biodegradable polymers is a sustainable and eco-conscious choice, some hurdles must be overcome. These challenges can be analyzed in subgroups, including insufficient awareness and how to increase it, the absence of regulations on biobased polymers, their usage and recyclability, the significantly higher production costs of bioplastics compared to conventional plastics, and inadequate plastic sorting systems, which raises the risk of contamination and renders plastics non-recyclable. Additionally, both bioplastics and conventional plastics pose concerns about generating microplastics.

The transition from conventional plastics to biobased alternatives is currently competitive given that conventional plastics have a well-established infrastructure and lower production costs. Developing a greener bioplastic system, especially medical grade, is intricate, laborious and expensive. Regardless of these challenges, a significant increase in the production and development of recycling systems that work on plastic waste is critical to meet the demand, particularly in the medical field.

All plastic materials form microplastics, but biobased-sourced microplastics are shorter-lived, making them less of a threat to the environment than conventional plastics. Considering this, manufacturers and everyone else using these polymers should address this microplastic formation problem. The more effective solution is to include these biobased polymers in the production-recycle loop. Consequently, the possibility of producing and scattering microplastics to the environment will be reduced and even eliminated. However, achieving this not only depends on the developments in recycling technology but also on the regulations and guidelines that are well established to ensure the proper recycling and end-of-life management of biodegradable biobased plastics. One important policy is the extended product responsibility of manufacturers, which ensures that the biobased plastics remain their liability even after post-production. These policies are crucial for manufacturers to address when a product must be produced according to its decomposition and reproduction standards. This comprehensive review highlights routes towards a greener medical field, emphasizing the transition from conventional fossil-based plastics to biobased and biodegradable alternatives. It underscores their potential benefits and challenges that hamper their widespread acceptance. To ensure a successful transition and adaptation of a circular and sustainable system, addressing existing gaps through policy development, increased research investment, and improved global recycling systems for a sustainable, circular future is essential.

Conflicts of interest

P. v. R. also is a co-founder, scientific advisor, and shareholder in BiomACS BV, a biomedical-oriented screening company. The authors declare no other conflict of interest. The authors declare no competing financial interest.

Data availability

No original data were produced in this study.

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