Rocznik Ochrona Środowiska

Volume 25 Year 2023 ISSN 2720-7501 pp. 128-140

https://doi.org/10.54740/ros.2023.013 open access

Received: June 2023 Accepted: July 2023 Published: July 2023

Sustainable Approaches to Plastics

Stanisław Frąckowiak

Faculty of Environmental Engineering, Wroclaw University of Science and Technology, Poland

https://orcid.org/0000-0002-9231-4140

corresponding author's e-mail: stanislaw.frackowiak@pwr.edu.pl

Abstract: Environmental concern and awareness have led to the development of different sustainable approaches to reduce the environmental impact of waste plastics. A brief literature review was conducted to evaluate recent challenges and emerging ideas on this topic. The two most noticeable approaches identified here are the introduction of biodegradable polymers as replacements for conventional plastics and recycling post-consumer waste plastics. The sustainable approach protects the environment, reducing energy consumption and greenhouse gas emissions.

Keywords: waste plastics, mechanical recycling, biopolymers, wastewater

1. Introduction

Plastic polymers have been with us for decades now. One cannot imagine life without all the everyday objects that surround us, in electronics, packaging, agriculture, automotive, medicine and others. Although plastics are produced in different varieties, which differ in properties depending on the type of polymer, additives, fillers, modifications (physical and chemical) etc., as a material class, their main advantages are low weight, high resistance to different degradation factors, low price and relatively cheap mass production.

However, right now, it is a well-known fact that those advantages are also considered a significant threat to the environment, including increasing problems in waste disposal, an increase in carbon dioxide emissions during incineration (contributing to the global warming effect), and the release of tiny plastic particles (called microplastics) into the soil and water, which have proven to have a negative impact on the wildlife. Microplastics tend to form large agglomerates, so they often do not float as expected. Instead, due to sedimentation, they are found beneath the water surface at various depths. Currently, there is plenty of research available on these particles on beaches and close to the shoreline. Investigating the seabed itself proves to be a challenging task. Thus much of the data concerning the deep sea is extrapolated from results that are easier to obtain. The impact on wildlife is mainly associated with the fact that marine life ingests these particles, which later accumulate in their digestive tracks. With each step in the food chain, the concentration of the microplastics increases. As mentioned before, plastics have a very long degradation period, so this problem cannot dissipate by itself in a reasonable period. The rise in unmanaged plastic waste has recently become a significant global concern.

One approach to reducing this threat is implementing a more sustainable approach to plastics (Rana et al. 2022). That means the current rate of development should be maintained while avoiding the depletion of natural resources for future generations. This goal is believed to be achieved, as it is a core principle of the Treaty on European Union and a priority objective for the Eu's internal and external policies. There are some basic rules for plastic materials to consider when determining if a polymer is sustainable. It should be manufactured from renewable feedstock, with minimal use of non-renewable resources and the reduction of potentially harmful environmental emissions (i.e. sewage water, greenhouse gasses and similar pollutants). At the end of its life cycle, it should be either removed in a controlled manner or reused (following the principles of reuse, reduce and recycle). One of the most promising groups of plastics are the ones based on biodegradable polymers, as they are typically derived from renewable feedstock and are biodegradable. Thus, they meet the two most distinctive criteria of the sustainable approach when it comes to polymeric materials.

2. Renewable Feedstock

When considering the criteria for selecting the feedstock type criteria, polymers obtained from natural sources can be classified into several groups. It is essential to mention that only the main groups represent the main categories, as currently, the field of such materials, especially considering polymers with inherent biodegradability, is undergoing extensive research. Additionally, there are numerous commercial products available in the market.

Table 1. Polymers obtained from renewable feedstock

Production method	Polymers	
directly extracted from the biomass	polysaccharides	starch – potatoes, corn, rice, wheat, starch derivatives
		cellulose – cotton, wood, flax, other fibre crops, cellulose derivatives
		chitosan/chitin
	proteins	animal – casein, whey, collagen, gelatin
		vegetable – soya, gluten
synthesised from bioderived monomers	poly (lactid acid) – PLA, where lactid acid is obtained, for example, by fermentation of starch	
polymers produced by microorganisms	poly (hydroxybutyric acid) – PHB	
	poly (hydroxyvaleric acid) – PHV	
	copolymers of PHB and PHV	
	bacterial cellulose	
conventional non-biodegradable polymers produced partially from the renewable feedstock	polypropylene (PP), polyethylene (PE), polyurethane (PU), polyamides (PA)	

As there are numerous applications of the polymers mentioned in Table 1, i.e. as packaging, the food industry, construction, medical applications and many others, it should be noted that this review mainly focuses on the sustainability aspect of these materials, their composites, and the current trends in their development.

2.1. Starch

Starch is a material that has been used by humankind for ages, mainly as a source of food. However, it is also used in the textile, packaging industry, and other sectors. Its wide popularity is associated chiefly due to its low price. Native starch is not a thermoplastic polymer; however, plasticisation (involving plasticisers, mainly water or glycerol) can transform it into one and processed using common processing equipment dedicated to other "conventional" plastics. This modified material is called thermoplastic starch (TPS). The first applications of starch as a biodegradable polymer that had the potential to replace polymers obtained from non-renewable resources at least partially were attempts to use starch as an additive to polyolefins in the 1970s (Otey 1976), mainly low-density polyethylene (Hakkarainen et al. 1997, Liu et al. 2003, Wang et al. 2004). The resulting material had a decreased elongation, deteriorated tensile strength and increased elastic modulus. However, its biodegradability was mainly unaffected because starch requires access to microorganisms and the presence of water to biodegrade. When immiscible starch was incorporated into polyethylene it efficiently blocked both factors. Currently, starch applications mainly consist of thermoplastic starch as a standalone material or as an additive to other biodegradable polymers, aiming to obtain fully biodegradable blends with a tailored set of properties. Processing methods for obtaining starch-based materials, mainly for packaging industry, can be listed as follows: film forming (De Paola et al. 2021, Kumar Malik et al. 2022), coating (Chi et al. 2020, Dai et al. 2020, Najafidoust et al. 2020, Oyom et al. 2022), foaming (Han et al. 2023, Hoc & Haznar-Garbacz 2021, Mort et al. 2022, Zhang & Xu 2022, Zubair et al., 2020) and extrusion (Babatunde et al. 2023, Huang et al. 2022, Rangira et al. 2020, Richter et al. 2022, Zhou et al. 2022). Each method listed has a specific range of applications dedicated to different products. However, on an industrial scale, the extrusion process is one of the most dominant ones as it allows to produce a continuous profile, sheet, rod or any other shape, depending on the extruder die construction. It can enable the in-situ, reactive modification of the processed starch, adding chemical modifiers, removing gaseous products, producing blends, etc. One of the most studied blends of starch is with biodegradable polyester polymers (mainly PLA and other polyesters) (Chauhan et al. 2021, Villadiego et al. 2022, Spiridon et al. 2020, Wang et al. 2021, Yang et al. 2023). Hu et al. (Hu et al. 2020) proposed using a well-known plasticizer for starch, polyethylene glycol (PEG), but with a rather interesting reactive blending approach. After participating in the esterification reaction, this approach allowed them to obtain a blend of TPS with PLA with a highly stable crosslinked/branched polyester on the starch surface to improve the compatibility between PLA and starch further. According to their findings, which significantly decreased the water absorption of developed materials and increased their stability, water absorption, is one of the main disadvantages of biodegradable polymers, particularly TPS. There are several methods to minimize this phenomenon, of which acetylation is the most widely used. Noivoil and Yoksan (Noivoil & Yoksan 2021) have recently developed a blend of PLA and acetylated TPS, which, as a result, has increased water vapour barrier properties and has the potential to be a fully biodegradable material for flexible packaging.

2.2. Cellulose

Cellulose is the most common form of carbon in biomass, accounting for 40-60 wt.% of the biomass, depending on the biomass source. It is a complex polysaccharide made of six-carbon sugar (glucose). Its crystalline structure makes it resistant to hydrolysis, the chemical reaction that releases simple, fermentable sugars from a polysaccharide. A typical cellulose-based processing chain consists of extraction (sources such as wood, bamboo, and other plants), processing (regenerated cellulose, pulp, derivatives, secondary chemicals), and product production (gels, membranes, films, fibres, composites). Its application field is broad, as it can be used in packaging, textiles, construction, membranes, coatings, different consumables, and others. Cellulose is produced in large quantities with different morphologies and sizes, depending on the type of processed biomass. What needs to be underlined is that one of the sources of obtaining cellulose is waste material from different processes, such as pre-harvest and post-harvest agricultural losses as well as waste from the food processing industry (Das & Singh 2004). Therefore, cellulose is a cheap material that has been extensively studied over the last few decades, both as a standalone polymer and as a filler for other biodegradable polymers.

Cellulose as a biopolymer has a broad field of applications, considering food packaging (Hadimani et al. 2023), medical (Yahya et al. 2020), different types of absorbents (Park et al. 2020), membranes (Samaniego & Espiritu 2022) and other (Dao et al. 2022, Fernandes et al. 2020, Lupașcu et al. 2022, Nguyen et al. 2022, Rizal et al. 2020). For composites based on different polymers, filled with naturally occurring or man-made cellulosic fibres, the number of researched applications is also very extensive. The mostly used biopolymers are previously mentioned biopolymers such a PLA, polyhydroxyalkanoates (PHAs), and starch-based plastics (Baghaei & Skrifvars 2020). Due to their unique properties, mostly characterized by high stiffness and low density, they have been extensively used in the packaging, automotive, and transport industry. Although it is not that easy to produce such composite, as one must consider the challenge of improving the interfacial compatibility between the polymer matrix and the hydrophilic cellulose fibers. This compatibility is crucial in achieving a biocomposite with favourable mechanical properties (Zhou et al. 2021). This is especially true for the PLA-cellulose composites, where weak interfacial adhesion could severely decrease the mechanical strength of the polymer matrix. Cui et al. (Cui et al. 2020) have adapted the cellulose as reinforcing fillers in PLA composite by modifying the cellulose surface with citric acid. The modified fillers exposed within the PLA matrix exhibited a good dispersion and reinforced-composites brought out the enhanced flexural modulus and stress. This suggests the compatibility between the fillers and PLA, by introducing carboxylic groups on the cellulose surface. Overall, these improvements greatly enchance the end properties of the developed composite. A similar approach, but with a different source of cellulose fibers (obtained from waste rubber wood) was presented by Ou et al. (Ou et al. 2021). In their study, rubber wood cellulose was effectively isolated, processed, and surface modified into acetylated cellulose and cellulose nanocrystals. Both of these materials show promise as reinforcing fillers for fabricating PLA-based composite films. However, the use of cellulose as a filler is not limited to biopolymers alone. There are many examples of incorporating such fillers into fossil-derived polymers such as polypropylene (PP), polyethylene (PE) or polyurethane (PU). Samadam et al. (Samadam et al. 2022) proposed three composites of cellulose and high density polyethylene (HDPE).

Based on tensile tests, it was concluded that increasing the cellulose content further decreases the material's tensile strength. With a limit value of 45% of cellulose content, HDPE's hardness increases along with its overall mechanical properties. Yu et al. (Yu et al. 2022) also used cellulose as a filler for conventional non-biodegradable plastic such as PU. Their findings were similar, as the addition of cellulosic filler increased the tensile strength of the composite while simultaneously reducing the strain rate.

2.3. Chitosan/chitin

Chitosan is obtained by deacytylation of chitin which is the second most abundant biopolymer in nature next to cellulose and is mainly found in invertebrates, fungi, and yeasts. Chitosan can be made from chitin by enzymatic or chemical processes. Due to the low cost and scalable mass production, the chemical process is favourable for producing chitosan for commercial use. Chitosan is a non-toxic, biodegradable, biocompatible material with many interesting chemical and physical properties and attractive biological functionalities, such as antimicrobial, antioxidant, antitumor activities, etc. (Xue & Wilson 2021). As a natural bio-active material that is broadly available and exhibits excellent antimicrobial activity, one of its highly recommended applications is in various types of different coatings, especially for food preservation in the packaging industry, cosmetics and biomedical purposes. (Bari et al. 2021, Gumienna & Górna 2021, Liu et al. 2021, Pal et al. 2021, Salmas et al. 2021a, Xue & Wilson 2021). It is especially suitable for food packaging applications as it is safe for human consumption (Al-Hilifi et al. 2023). Several approaches have been investigated to improve its properties for different applications and functions, including modifications using various additives, blend processing with biopolymers and other fillers. These modifications are usually aimed at enhancing the barrier properties, which are significant factors for packaging materials (Andonegi et al. 2020, Rodriguez Llanos et al. 2021, Salmas et al. 2021b). The sustainability aspect of chitosan is extensive. It can be used as a plant growth promoter along with its antimicrobial activity (Maluin & Hussein 2020). It can serve as a biomimetic structure for tissue engineering in medical applications, showing good biocompatibility. Scalera et al. (Scalera et al. 2021) showed that chitosan can be used as a potential electroactive scaffold for endogenous tissue regeneration. Additionally, chitosan beads can be used for water purification in wastewater treatment (Balakrishnan et al. 2023). It is worth mentioning that it is also used in electronics due to its optimal piezoelectric properties (Marasco et al. 2023). Therefore due to its wide range of applications, being abundant, biodegradable and biocompatible, chitosan can be considered one of the most promising materials in terms of a sustainable approach towards plastic materials.

2.4. Poly (lactid acid)

PLA is a thermoplastic polymer that is 100% biodegradable. It is produced from renewable raw materials such as corn, sugar beets, etc. Its basic mechanical properties can be somewhat altered, making it flexible or stiff depending on the application criteria. It can be processed using standard methods dedicated to "conventional" petroleum-based polymers. Depending on the desired set of properties, it can be mixed with all kinds of additives, including stabilizers, plasticizers and others suitable for most polymers. When mentioning its practical properties, it needs to be noted that it also presents a decent UV radiation resistance. Therefore, its application range is not limited to indoor, sun-insulated products, a typical problem with nature-based materials (Czechowski et al. 2022, Shang et al. 2022).

Although PLA is biodegradable, products made of PLA have a long shelf life and can be stored for years. The biodegradation of PLA is mainly a two-step process. First, hydrolytic degradation weakens the polymer structure and reduces its molecular weight before microorganisms attack the polymer's inner structure. When a bottle made of PLA is landfilled, it undergoes at a similar time as conventional plastics. However, when introduced to an industrial composting facility with an elevated temperature of 60°C and a high concentration of given microorganisms, the degradation time can be as short as 90 days (Brdlík et al. 2023a, Fogašová et al. 2022, Lu et al. 2023).

PLA, as a polymer material, was developed in the early 1920s of the XXth century. Its first applications were in small-scale medical applications due to its excellent biocompatibility, as its basic building block or monomer (lactid acid) is a naturally occurring substance in the human body (DeStefano et al. 2020). It was not until the beginning of the XXIst century that the first full-scale processing plant was founded under the trade name of NatureWorks™ in the USA. Currently, its main applications include the textile industry ("breathing"), medicine (threads, stents, tissue engineering), personal hygiene products, packaging, compostable bags, and cutlery and crockery for serving food (Bikiaris et al. 2023, Li et al. 2023, Swetha et al. 2023, Wu et al. 2022). The current production is estimated to be over 300 KT annually, with NatureWorks (USA) and Total Corbion (Thailand) installations covering around 62% of the total production (Rajeshkumar et al. 2021).

The sustainability of the PLA polymer is mainly associated with its biodegradation, recyclability, and the potential to reduce greenhouse gasses. The latter is because the CO_2 emissions during the production stage are balanced by the intake of the same gasses during the agricultural phase when the crops have absorbed the CO_2 during the photosynthesis process (Morão & de Bie 2019, Rezvani Ghomi et al. 2021). However, regarding the apparent advantages of PLA and its growing market demands along with production levels, this polymer has limitations. Firstly, its elongation rate is similar to the polystyrene, ca. 5%. This excludes all the applications that require elastic materials with good energy dissipation ability. It can be plasticized to improve significantly its elongation at break parameter (approximately to 80-150%); however, plasticized polymers are naturally less stable over time and prone to the plasticizer loss, inevitably decreasing their mechanical properties (Brdlík et al. 2023b, Halloran et al. 2022, Murariu et al. 2022, Perez-Nakai et al. 2023, Tábi et al. 2022). Secondly, its thermal stability is about 60°C, limiting its applications in the fields such as hot beverages. This parameter can be increased by increasing the crystallinity or via an annealing process, raising the Heat Deflection Temperature (HDT) from 58 to 160°C (Pazhamannil & Edacherian 2022, Zhao et al., 2022). The third main drawback is the high gas permeability, which reduces its gas barrier properties. However, this can have a beneficial impact, as some applications require the migration of certain gaseous particles, i.e. water vapor, which is crucial for prolonging the shelf life of fresh foods (Abd Al-Ghani et al. 2021).

Despite the listed drawbacks, PLA is receiving a lot of attention from research groups worldwide due to its well-established market value and production, which demonstrated a compound annual growth rate of 16,3% in 2020. Compared with other biodegradable plastic and plastics derived from natural feedstock, PLA is currently by far the most crucial plastic available.

2.5. Biopolymers produced by microorganisms

Bioplastics produced by microorganisms, often called microbial plastics, comprise several groups of polymers. Among these groups, bacterial polysaccharides and bacterial polyesters, such as poly(hydroxyalkanoates) (PHA), have found the most noticeable application and commercial availability. Poly(hydroxybutyrate) (PHB) and poly(hydroxybutyrate-co-valerate) (PHBV) are the most common, judging on their application potential. It is important to note that while these offer an interesting and sustainable alternative to conventional and other plastics, they represent a relatively small niche in the overall polymers in terms of production quota. As they are biodegradable and biocompatible, their main application range is medical applications such as drug delivery, tissue engineering, and other environmental applications like membranes, with a portion of the packaging industry as well.

Microbial polymers are produced by selected bacteria under controlled conditions, serving mainly as energy reserves for the organisms mentioned. Their typical production cycle consists of starting a master batch of bacterial colonies, after a sufficient volume of bacteria is reached, they are transferred to a larger vessel where the primary production process occurs. After a given time, the food source is reduced, forcing the microorganisms to gather carbon reserves that are stored intracellularly. The next step involves extracting the stored polymers from the bacteria, usually using hot solvents, which are later recovered. Finally, the polymer is removed from the solution in a precipitation vessel and subsequently dried and purified (Samadhiya et al. 2022).

The production system can be modified and/or engineered to produce different polymers or copolymers. However, compared to other materials with similar properties, their cost is still relatively high, limiting their commercial potential. Nevertheless, there are laboratory/small-scale approaches that utilize different and less expensive feedstocks, mainly waste materials such as waste plants oils, waste animal fats, municipal waste, pulp industry, sugar industry, coffee industry and other feedstocks suitable for microbial fermentation, which is less expensive compared to the current ones (Arcos-Hernandez et al. 2013, Ganesh Saratale et al. 2021, Ray et al. 2016, Rhu et al. 2003, Wróblewska-Krepsztul et al. 2018). The main drawback in the large-scale commercialization of PHA and other microbial polymers is their production cost, which ranges from 8000-16000 US$ per Mt. This cost is about three times higher than the production cost of oil-based polymers and around 50% of that price is attributed to the cost of the food source for the microorganisms (Kosseva & Rusbandi 2018).

There are several companies currently involved in PHA commercial production, among which are Bio-on (Italy), Poly-Ferm (Canada), Danimer Scientific (USA), and Tianjin GreenBio Materials (China). While most of the production quota is allocated to manufacturing the previously mentioned medical applications (such as sutures, wound dressing, surgical meshes, nerve grafting etc.), a relatively small portion is utilized for packaging applications, mainly food contact films, straws, and different flexible products. As proposed by Manikandan et al. (Manikandan et al. 2020), a PHB/graphene nanocomposite was developed with high biodegradability and improved barrier properties for food packaging applications. They have found that the developed material significantly improved the shelf life of the investigated products, in addition to negligible cytotoxic effect. Similar findings were reported by Popa et al. (Popa et al. 2022), who have stated, based on their research, that common processing techniques used for plastics, such as the addition of plasticizers or fillers through reactive blending or extrusion, can significantly improve the end properties of PHB in terms of mechanical strength along with ductility. The shelf life of short-term food products can be enhanced by up to 10 days (i.e. brown bread) by implementing a composite film produced from PHB with inherent antimicrobial properties, with the addition of nano-silica and essential oils (Mittal et al. 2023).

While still more expensive than their fossil-derived counterparts, microbial polymers undoubtedly have a considerable potential for many different, sustainable applications. As naturally derived as they can get, they present an additional way to reduce environmental pollution and greenhouse gas emissions. In addition, food packaging products with increased antimicrobial properties can reduce food spoilage and help preserve freshness.

2.6. Non-biodegradable polymers

Non-biodegradable, conventional polymers can be partially derived from renewable resources. They do not cover the biodegradation property, their properties are the same as their fully fossil-based counterparts. In the production cycle, bioethanol from sugar fermentation is used instead of ethanol. The most common polymers available on the market are the partially bio-derived versions of common polymers such as polyethylene, polyurethane, poly(vinyl chloride) (PVC), polyamide (PA), poly(ethylene terephthalate) (PET) and others.

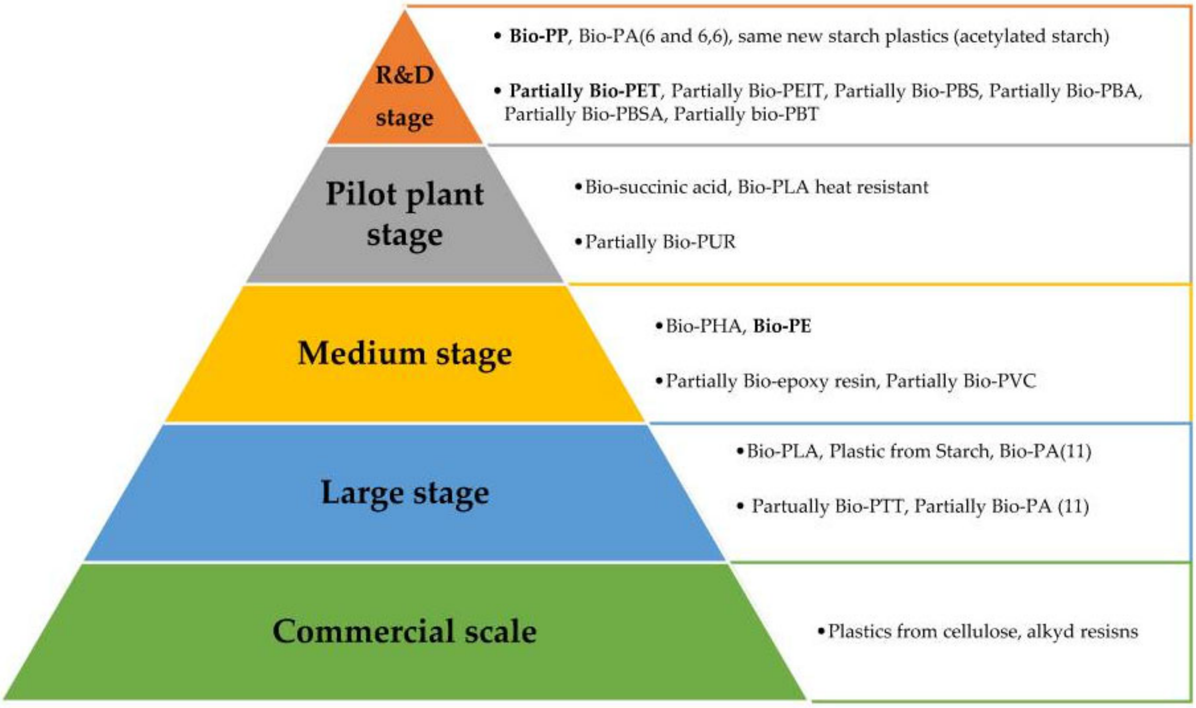

Fig. 1. Development stages for emerging bio-based polymers (Siracusa & Blanco 2020)

Most non-biodegradable polymers from partially renewable resources remain limited in the market as their production has been commercialized on a large scale only for PA (11) and PE, as shown in Fig. 1.

3. Recycling and Sustainable Applications of Plastics

As previously mentioned, conventional plastic materials do not dissipate in the environment. Since biodegradable polymers are still less favourable by the market due to their relatively high price, recycling plastics is still an important issue. The annual worldwide plastic production is estimated at 415 million tons, of which about 10% is obtained from recyclable materials (Maitlo et al. 2022). There are three main methods of recycling plastics on an industrial scale. The first method is mechanical recycling, when a collected, separated and cleaned stream of homogenous polymer waste is converted into granulates, which can be further processed using different techniques to create new products. The second method is feedstock or chemical recycling when plastics are converted back into their original monomers or other valuable chemicals. The third approach is energy recovery, where plastic waste is incinerated, simultaneously generating energy. A scheme presenting the typical life cycle of plastic, particularly with plastic packaging, is shown in Fig. 2. Presented numbers indicate the mean percentage values of each type of material disposal method.

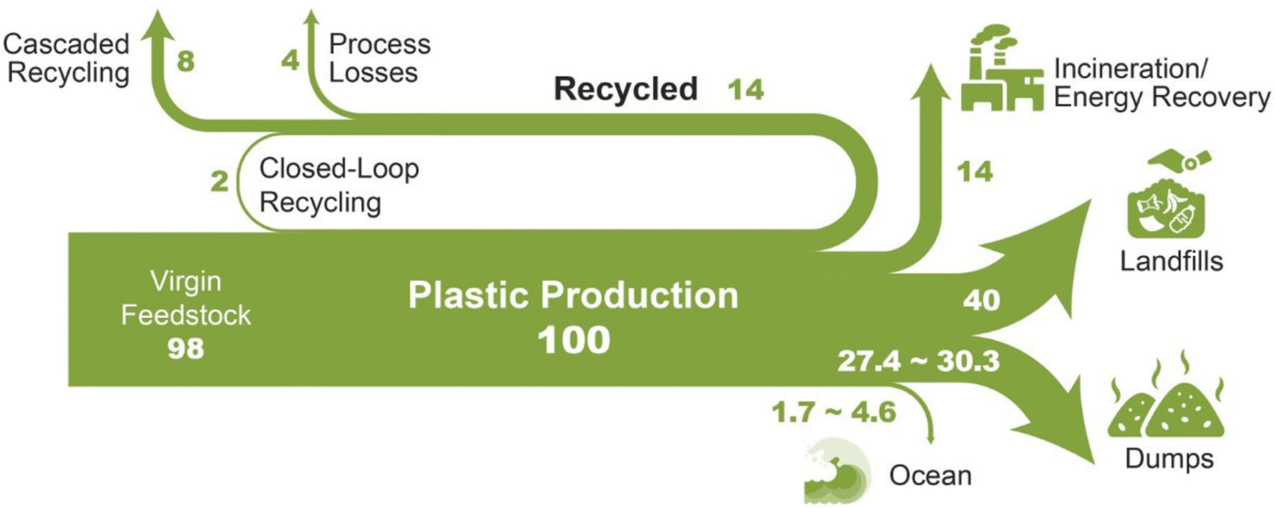

Fig. 2. Life cycle of plastic packaging (Li et al. 2022)

Each of the methods has its pros and cons. The factors that need to be considered are the economic feasibility, material degradation during the recycling process, end product properties, and range of applications. Because plastics are not a single material, but a variety of different polymers, immiscible by nature, the simple mixing of post-consumer waste is out of the question. While the products are marked, stating which polymer is the main component, some other additives or materials must be considered. These include colour additives, UV stabilizers, flame retardants and many more. For achieving specific properties like increased barrier properties, ultra-thin layers of less permeable materials (polymers or aluminium) are used. Therefore mechanical recycling, whereas simple, has its limitations, as a homogenous stream of a single polymer needs to be implemented into the extruder to obtain recyclate with the desired properties. Chemical recycling is much less demanding regarding waste stream quality, similar to energy recovery. As a result, plastic products that are not feasible for mechanical recycling, i.e. thin films, multilayered materials, and multi-component products, are typically recycled in this manner.

To improve the so-called recyclability of different plastic products, they should be designed with something called "eco-design" in mind. Such products should be made of a single polymer or a blend of polymers. Such attempts have already been made; i.e. drinking bottles are made of PET, but their caps are made of PP. Two approaches have been introduced to achieve easy and cost-effective recycling. Firstly, using the same (PET) polymer for both the bottle and the cap has proven to be challenging due to problems with sufficient sealing. Secondly, introducing a small bottle-cap connector to prevent their separation and minimise the risk of the cap getting lost on its way to the recycling facility. The material composition should also avoid using difficult to remove or cover colourants, for example, carbon black. Another aspect of product design that needs to be considered is the product's shape; for example, containers should be designed to allow easy removal of their content (food, cosmetics, etc.). Suppose there are foreign materials needed on the plastic product. In that case, they should be made of the same material as the main component or material easily compatible with when coextruded. Adhesives and similar substances should be easy to remove during the pre-recycling preparations.

There are many different areas of applications for plastic waste. The most common ones are as follows (Table 2).

Table 2. Selected fields of applications for plastic waste

Applications	Type of plastics	Reference
artificial wood composites	PP	(Burgada et al. 2021)
concrete additives, construction elements	LDPE, HDPE, PET, PP	(Alqahtani et al. 2021, Belmokaddem et al. 2020, Jain et al. 2022, Khan et al. 2021)
bituminous mixes, asphalt additives	LDPE, PP, PA	(Aldagari et al. 2022, Almeida et al. 2020, Haider et al. 2020, Krawczyk et al. 2022, Prata et al. 2021)
wastewater filters	LDPE, PET, PA, PP	(Dorji et al. 2022, Kumari et al. 2022, Pan et al. 2022)
fuel	HDPE, LDPE, PP, PET	(Alam et al. 2022, Fahim et al. 2021, Ghodke et al. 2023, Kumar Jha & Kannan 2021, Nakaji et al. 2021, Papari et al. 2021)

The textile industry produces a significant amount of plastic waste; however, the fibre-to-fibre recycling of such waste is relatively scarce as the process is not economically feasible. This is due to several key requirements that a textile fibre needs to fulfil. The material and its usual coating need to withstand stress from wear and tear, provide moisture and temperature regulation in footwear, in most applications, insulation from external factors, and release body heat. Of course, in the case of textiles, they have to be fashionable (Maitlo et al. 2022). That is why there are only a few publications on textile recycling. On the other hand, construction applications are being investigated on a much larger scale. This is mainly because it is much easier to implement most of the plastic waste in the form of a fine powder or fibre as a reinforcement to commonly used construction materials, i.e., concrete or a thermoset resin (Awoyera & Adesina 2020). It has been found that plastic waste can be used in cementitious compositions as a binder, aggregate, or fibre, resulting in significant improvements to their performance (Jawaid et al. 2023). If not used as a filler, recycled plastics can be shaped into construction elements, such as bricks. Jain et al. (Jain et al. 2022) have proposed a brick material consisting of a mixture of different waste polymers, including HDPE, low-density polyethylene (LDPE) and PET. And while the mechanical properties of the obtained elements in terms of compressive strength could not surpass those of concrete, they achieved higher compressive strength than usual or fly ash bricks. Another interesting research path is the development of filters for wastewater treatment obtained from recycled plastic waste. This approach was investigated by Ilyas et al. (Ilyas et al. 2022), where they have proposed a filter made of waste PET converted to carbonaceous adsorbents for removing potentially poisonous elements, such as chromium, copper and lead. Furthermore, a very promising and obvious choice for recycling plastic waste is its conversion into liquid fuel, known as liquefaction, which can also be divided into pyrolysis and hydrothermal liquefaction. Jiao et al. (Jiao et al. 2020) have proposed the selective conversion of various waste plastics into C2 fuels under simulated natural environment conditions. What is especially exciting is that the waste polymers used were PE, PP and PVC, although the presented studies were of a preliminary status.

4. Conclusions

In summary, it can be concluded that addressing the issue of plastic waste plastics requires the adoption of more sustainable approaches. Bioplastics designed to dissipate after their end of life are one such approach as a substitute for petroleum-based synthetic polymers that remain in the environment for extended periods. Different sustainable and biodegradable materials have been developed on a smaller scale, with steady growth to cope with the nondegradable plastics. Based on the review performed, the current biodegradable polymers have not reached a significant market share mainly due to their high production costs in comparison with their conventional, non-renewable counterparts. Nonetheless, there are several specific application fields where these materials are difficult to replace (i.e. medicine), and they can serve as a driving force to further increase the production of biopolymers.

Therefore, large-scale recycling of produced plastics is required to reduce the threat of waste plastics. Producing partially biobased polymers does not directly address plastic waste removal but rather helps to diversify the feedstock and decrease the dependence on fossil energy sources.

Based on the conducted literature survey, the well-known recycling process is still being investigated by many research groups to decrease the environmental burden of these materials further. The new end-products obtained from recyclates, along with new processing technologies and more cost-effective feedstock collection, offer functional and environmental benefits. Additionally, they contribute to the economic aspect and resource circularity, providing added value.

References

Abd Al-Ghani, M.M., Azzam, R.A., Madkour, T.M. (2021). Design and Development of Enhanced Antimicrobial Breathable Biodegradable Polymeric Films for Food Packaging Applications. *Polymers*, *13*(20), 3527. https://doi.org/10.3390/polym13203527

Alam, S.S., Churkunti, P.R., Depcik, C. (2022). Comparison of waste plastic fuel, waste cooking oil biodiesel, and ultra-low sulfur diesel using a Well-to-Exhaust framework. *International Journal of Environmental Science and Technology*, *19*(7), 5857-5876. https://doi.org/10.1007/s13762-021-03552-3

Aldagari, S., Kabir, S.F., Fini, E.H. (2022). A comparative study on efficacy of waste plastic and waste Rubberin bitumen. *Construction and Building Materials*, *325*, 126724. https://doi.org/10.1016/j.conbuildmat.2022.126724

Al-Hilifi, S.A., Al-Ibresam, O.T., Al-Hatim, R.R., Al-Ali, R.M., Maslekar, N., Yao, Y., Agarwal, V. (2023). Development of Chitosan/Whey Protein Hydrolysate Composite Films for Food Packaging Application. *Journal of Composites Science*, *7*(3), 94. https://doi.org/10.3390/jcs7030094

Almeida, A., Capitão, S., Bandeira, R., Fonseca, M., Picado-Santos, L. (2020). Performance of AC mixtures containing flakes of LDPE plastic film collected from urban waste considering ageing. *Construction and Building Materials*, *232*, 117253. https://doi.org/10.1016/j.conbuildmat.2019.117253

Alqahtani, F.K., Abotaleb, I.S., ElMenshawy, M. (2021). Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates. *Journal of Building Engineering*, *40*, 102670. https://doi.org/10.1016/j.jobe.2021.102670

Andonegi, M., Heras, K.L., Santos-Vizcaíno, E., Igartua, M., Hernandez, R.M., de la Caba, K., Guerrero, P. (2020). Structure-properties relationship of chitosan/collagen films with potential for biomedical applications. *Carbohydrate Polymers*, *237*, 116159. https://doi.org/10.1016/j.carbpol.2020.116159

Arcos-Hernandez, M.V., Pratt, S., Laycock, B., Johansson, P., Werker, A., Lant, P.A. (2013). Waste Activated Sludge as Biomass for Production of Commercial-Grade Polyhydroxyalkanoate (PHA). *Waste and Biomass Valorization*, *4*(1), 117-127. https://doi.org/10.1007/s12649-012-9165-z

Awoyera, P.O., Adesina, A. (2020). Plastic wastes to construction products: Status, limitations and future perspective. *Case Studies in Construction Materials*, *12*, e00330. https://doi.org/10.1016/j.cscm.2020.e00330

Babatunde, O.O., Cargo-Froom, C.L., Ai, Y., Newkirk, R.W., Marinangeli, C.P.F., Shoveller, A.K., Columbus, D.A. (2023). Extrusion effects on the starch and fibre composition of Canadian pulses. *Canadian Journal of Animal Science*. https://doi.org/10.1139/cjas-2022-0127

Baghaei, B., Skrifvars, M. (2020). All-Cellulose Composites: A Review of Recent Studies on Structure, Properties and Applications. *Molecules*, *25*(12), 2836. https://doi.org/10.3390/molecules25122836

Balakrishnan, A., Appunni, S., Chinthala, M., Jacob, M.M., Vo, D.-V. N., Reddy, S.S., Kunnel, E.S. (2023). Chitosan-based beads as sustainable adsorbents for wastewater remediation: A review. *Environmental Chemistry Letters*, *21*(3), 1881-1905. https://doi.org/10.1007/s10311-023-01563-9

Bari, A., Hussain, S., Hussain, M., Ali, N., Malik, A.A. (2021). Preparation and Characterization of Chitosan and Ethylene Glycol Based Chitosan Films. *Journal of the Pakistan Institute of Chemical Engineers*, *49*(1), 21-32. https://doi.org/10.54693/piche.04913

Belmokaddem, M., Mahi, A., Senhadji, Y., Pekmezci, B.Y. (2020). Mechanical and physical properties and morphology of concrete containing plastic waste as aggregate. *Construction and Building Materials*, *257*, 119559. https://doi.org/10.1016/j.conbuildmat.2020.119559

Bikiaris, N.D., Koumentakou, I., Samiotaki, C., Meimaroglou, D., Varytimidou, D., Karatza, A., … Papageorgiou, G.Z. (2023). Recent Advances in the Investigation of Poly(lactic acid) (PLA) Nanocomposites: Incorporation of Various Nanofillers and their Properties and Applications. *Polymers*, *15*(5), 1196. https://doi.org/10.3390/polym15051196

Brdlík, P., Novák, J., Borůvka, M., Běhálek, L., Lenfeld, P. (2023a). The Influence of Plasticizers and Accelerated Ageing on Biodegradation of PLA under Controlled Composting Conditions. *Polymers*, *15*(1), 140. https://doi.org/10.3390/polym15010140

Brdlík, P., Novák, J., Borůvka, M., Běhálek, L., Lenfeld, P. (2023b). The Influence of Plasticizers and Accelerated Ageing on Biodegradation of PLA under Controlled Composting Conditions. *Polymers*, *15*(1), 140. https://doi.org/10.3390/polym15010140

Burgada, F., Fages, E., Quiles-Carrillo, L., Lascano, D., Ivorra-Martinez, J., Arrieta, M.P., Fenollar, O. (2021). Upgrading Recycled Polypropylene from Textile Wastes in Wood Plastic Composites with Short Hemp Fiber. *Polymers*, *13*(8), 1248. https://doi.org/10.3390/polym13081248

Chauhan, S., Raghu, N., Raj, A. (2021). Effect of maleic anhydride grafted polylactic acid concentration on mechanical and thermal properties of thermoplasticized starch filled polylactic acid blends. *Polymers and Polymer Composites*, *29*(9_suppl), S400-S410. https://doi.org/10.1177/09673911211004194

Chi, K., Wang, H., Catchmark, J.M. (2020). Sustainable starch-based barrier coatings for packaging applications. *Food Hydrocolloids*, *103*, 105696. https://doi.org/10.1016/j.foodhyd.2020.105696

Cui, X., Ozaki, A., Asoh, T.-A., Uyama, H. (2020). Cellulose modified by citric acid reinforced Poly(lactic acid) resin as fillers. *Polymer Degradation and Stability*, *175*, 109118. https://doi.org/10.1016/j.polymdegradstab.2020.109118

Czechowski, L., Kedziora, S., Museyibov, E., Schlienz, M., Szatkowski, P., Szatkowska, M., Gralewski, J. (2022). Influence of UV Ageing on Properties of Printed PLA Containing Graphene Nanopowder. *Materials*, *15*(22), 8135. https://doi.org/10.3390/ma15228135

Dai, L., Zhang, J., Cheng, F. (2020). Crosslinked starch-based edible coating reinforced by starch nanocrystals and its preservation effect on graded Huangguan pears. *Food Chemistry*, *311*, 125891. https://doi.org/10.1016/j.foodchem.2019.125891

Dao, D.N., Le, P.H., Do, D.X., Dang, T.M. Q., Nguyen, S.K., Nguyen, V. (2022). Pectin and cellulose extracted from coffee pulps and their potential in formulating biopolymer films. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02339-x

Das, H., Singh, S.K. (2004). Useful byproducts from cellulosic wastes of agriculture and food industry – A critical appraisal. *Critical Reviews in Food Science and Nutrition*, *44*(2), 77-89. https://doi.org/10.1080/10408690490424630

De Paola, M.G., Paletta, R., Lopresto, C.G., Lio, G.E., De Luca, A., Chakraborty, S., Calabrò, V. (2021). Stability of Film-Forming Dispersions: Affects the Morphology and Optical Properties of Polymeric Films. *Polymers*, *13*(9), 1464. https://doi.org/10.3390/polym13091464

DeStefano, V., Khan, S., Tabada, A. (2020). Applications of PLA in modern medicine. *Engineered Regeneration*, *1*, 76-87. https://doi.org/10.1016/j.engreg.2020.08.002

Dorji, U., Dorji, P., Shon, H., Badeti, U., Dorji, C., Wangmo, C., … Phuntsho, S. (2022). On-site domestic wastewater treatment system using shredded waste plastic bottles as biofilter media: Pilot-scale study on effluent standards in Bhutan. *Chemosphere*, *286*, 131729. https://doi.org/10.1016/j.chemosphere.2021.131729

Fahim, I., Mohsen, O., ElKayaly, D. (2021). Production of Fuel from Plastic Waste: A Feasible Business. *Polymers*, *13*(6), 915. https://doi.org/10.3390/polym13060915

Fernandes, I. de A.A., Pedro, A.C., Ribeiro, V.R., Bortolini, D.G., Ozaki, M.S.C., Maciel, G.M., Haminiuk, C.W.I. (2020). Bacterial cellulose: From production optimization to new applications. *International Journal of Biological Macromolecules*, *164*, 2598-2611. https://doi.org/10.1016/j.ijbiomac.2020.07.255

Fogašová, M., Figalla, S., Danišová, L., Medlenová, E., Hlaváčiková, S., Vanovčanová, Z., … Kadlečková, M. (2022). PLA/PHB-Based Materials Fully Biodegradable under Both Industrial and Home-Composting Conditions. *Polymers*, *14*(19), 4113. https://doi.org/10.3390/polym14194113

Ganesh Saratale, R., Cho, S.-K., Dattatraya Saratale, G., Kadam, A. A., Ghodake, G. S., Kumar, M., … Seung Shin, H. (2021). A comprehensive overview and recent advances on polyhydroxyalkanoates (PHA) production using various organic waste streams. *Bioresource Technology*, *325*, 124685. https://doi.org/10.1016/j.biortech.2021.124685

Ghodke, P.K., Sharma, A.K., Moorthy, K., Chen, W.-H., Patel, A., Matsakas, L. (2023). Experimental Investigation on Pyrolysis of Domestic Plastic Wastes for Fuel Grade Hydrocarbons. *Processes*, *11*(1), 71. https://doi.org/10.3390/pr11010071

Gumienna, M., Górna, B. (2021). Antimicrobial Food Packaging with Biodegradable Polymers and Bacteriocins. *Molecules*, *26*(12), 3735. https://doi.org/10.3390/molecules26123735

Hadimani, S., Supriya, D., Roopa, K., Soujanya, S.K., Rakshata, V., Netravati, A., … Jogaiah, S. (2023). Biodegradable hybrid biopolymer film based on carboxy methyl cellulose and selenium nanoparticles with antifungal properties to enhance grapes shelf life. *International Journal of Biological Macromolecules*, *237*, 124076. https://doi.org/10.1016/j.ijbiomac.2023.124076

Haider, S., Hafeez, I., Jamal, Ullah, R. (2020). Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures. *Construction and Building Materials*, *235*, 117496. https://doi.org/10.1016/j.conbuildmat.2019.117496

Hakkarainen, M., Albertsson, A.-C., Karlsson, S. (1997). Susceptibility of starch-filled and starch-based LDPE to oxygen in water and air. *Journal of Applied Polymer Science*, *66*(5), 959-967. https://doi.org/10.1002/(SICI)1097-4628(19971031)66:5<959::AID-APP15>3.0.CO;2-I

Halloran, M.W., Danielczak, L., Nicell, J.A., Leask, R.L., Marić, M. (2022). Highly Flexible Polylactide Food Packaging Plasticized with Non-toxic, Biosourced Glycerol Plasticizers. *ACS Applied Polymer Materials*, *4*(5), 3608-3617. https://doi.org/10.1021/acsapm.2c00172

Han, J.H., Lee, J., Kim, S.K., Kang, D., Park, H.B., Shim, J.K. (2023). Impact of the Amylose/Amylopectin Ratio of Starch-Based Foams on Foaming Behavior, Mechanical Properties, and Thermal Insulation Performance. *ACS Sustainable Chemistry & Engineering*, *11*(7), 2968-2977. https://doi.org/10.1021/acssuschemeng.2c06505

Hoc, D., Haznar-Garbacz, D. (2021). Foams as unique drug delivery systems. *European Journal of Pharmaceutics and Biopharmaceutics*, *167*, 73-82. https://doi.org/10.1016/j.ejpb.2021.07.012

Hu, H., Xu, A., Zhang, D., Zhou, W., Peng, S., Zhao, X. (2020). High-Toughness Poly(lactic Acid)/Starch Blends Prepared through Reactive Blending Plasticization and Compatibilization. *Molecules*, *25*(24), 5951. https://doi.org/10.3390/molecules25245951

Huang, X., Liu, H., Ma, Y., Mai, S., Li, C. (2022). Effects of Extrusion on Starch Molecular Degradation, Order–Disorder Structural Transition and Digestibility – A Review. *Foods*, *11*(16), 2538. https://doi.org/10.3390/foods11162538

Ilyas, M., Khan, H., Ahmad, W. (2022). Conversion of waste plastics into carbonaceous adsorbents and their application for wastewater treatment. *International Journal of Environmental Analytical Chemistry*, *0*(0), 1-19. https://doi.org/10.1080/03067319.2022.2062571

Jain, D., Bhadauria, S.S., Kushwah, S.S. (2022). An experimental study of utilization of plastic waste for manufacturing of composite construction material. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-04447-7

Jawaid, M., Singh, B., Kian, L.K., Zaki, S.A., Radzi, A.M. (2023). Processing techniques on plastic waste materials for construction and building applications. *Current Opinion in Green and Sustainable Chemistry*, *40*, 100761. https://doi.org/10.1016/j.cogsc.2023.100761

Jiao, X., Zheng, K., Chen, Q., Li, X., Li, Y., Shao, W., … Xie, Y. (2020). Photocatalytic Conversion of Waste Plastics into C2 Fuels under Simulated Natural Environment Conditions. *Angewandte Chemie International Edition*, *59*(36), 15497-15501. https://doi.org/10.1002/anie.201915766

Khan, M.I., Sutanto, M.H., Napiah, M.B., Khan, K., Rafiq, W. (2021). Design optimization and statistical modeling of cementitious grout containing irradiated plastic waste and silica fume using response surface methodology. *Construction and Building Materials*, *271*, 121504. https://doi.org/10.1016/j.conbuildmat.2020.121504

Kosseva, M.R., Rusbandi, E. (2018). Trends in the biomanufacture of polyhydroxyalkanoates with focus on downstream processing. *International Journal of Biological Macromolecules*, *107*, 762-778. https://doi.org/10.1016/j.ijbiomac.2017.09.054

Krawczyk, B., Mackiewicz, P., Dobrucki, D. (2022). Use of plastic waste in materials for road pavement construction and improved subgrade. *Roads and Bridges – Drogi i Mosty*, *21*(3), 203-216.

Kumar Jha, K., Kannan, T.T.M. (2021). Recycling of plastic waste into fuel by pyrolysis – A review. *Materials Today: Proceedings*, *37*, 3718-3720. https://doi.org/10.1016/j.matpr.2020.10.181

Kumar Malik, M., Kumar, T., Kumar, V., Singh, J., Kumar Singh, R., Saini, K. (2022). Sustainable, highly foldable, eco-friendly films from Mandua starch derivative. *Sustainable Energy Technologies and Assessments*, *53*, 102398. https://doi.org/10.1016/j.seta.2022.102398

Kumari, M., Chaudhary, G.R., Chaudhary, S., Umar, A. (2022). Transformation of solid plastic waste to activated carbon fibres for wastewater treatment. *Chemosphere*, *294*, 133692. https://doi.org/10.1016/j.chemosphere.2022.133692

Li, H., A. Aguirre-Villegas, H., D. Allen, R., Bai, X., H. Benson, C., T. Beckham, G., … W. Huber, G. (2022). Expanding plastics recycling technologies: Chemical aspects, technology status and challenges. *Green Chemistry*, *24*(23), 8899-9002. https://doi.org/10.1039/D2GC02588D

Li, X., Lin, Y., Liu, M., Meng, L., Li, C. (2023). A review of research and application of polylactic acid composites. *Journal of Applied Polymer Science*, *140*(7), e53477. https://doi.org/10.1002/app.53477

Liu, J., Huang, J., Hu, Z., Li, G., Hu, L., Chen, X., Hu, Y. (2021). Chitosan-based films with antioxidant of bamboo leaves and ZnO nanoparticles for application in active food packaging. *International Journal of Biological Macromolecules*, *189*, 363-369. https://doi.org/10.1016/j.ijbiomac.2021.08.136

Liu, W., Wang, Y.-J., Sun, Z. (2003). Effects of polyethylene-grafted maleic anhydride (PE-g-MA) on thermal properties, morphology, and tensile properties of low-density polyethylene (LDPE) and corn starch blends. *Journal of Applied Polymer Science*, *88*(13), 2904-2911. https://doi.org/10.1002/app.11965

Lu, J., Qiu, Y., Muhmood, A., Zhang, L., Wang, P., Ren, L. (2023). Appraising co-composting efficiency of biodegradable plastic bags and food wastes: Assessment microplastics morphology, greenhouse gas emissions, and changes in microbial community. *Science of The Total Environment*, *875*, 162356. https://doi.org/10.1016/j.scitotenv.2023.162356

Lupașcu, R.E., Ghica, M.V., Dinu-Pîrvu, C.-E., Popa, L., Velescu, B. Ștefan, Arsene, A. L. (2022). An Overview Regarding Microbial Aspects of Production and Applications of Bacterial Cellulose. *Materials*, *15*(2), 676. https://doi.org/10.3390/ma15020676

Maitlo, G., Ali, I., Maitlo, H.A., Ali, S., Unar, I.N., Ahmad, M.B., … Afridi, M.N. (2022). Plastic Waste Recycling, Applications, and Future Prospects for a Sustainable Environment. *Sustainability*, *14*(18), 11637. https://doi.org/10.3390/su141811637

Maluin, F.N., Hussein, M.Z. (2020). Chitosan-Based Agronanochemicals as a Sustainable Alternative in Crop Protection. *Molecules*, *25*(7), 1611. https://doi.org/10.3390/molecules25071611

Manikandan, N.A., Pakshirajan, K., Pugazhenthi, G. (2020). Preparation and characterization of environmentally safe and highly biodegradable microbial polyhydroxybutyrate (PHB) based graphene nanocomposites for potential food packaging applications. *International Journal of Biological Macromolecules*, *154*, 866-877. https://doi.org/10.1016/j.ijbiomac.2020.03.084

Marasco, I., Niro, G., de Marzo, G., Rizzi, F., D'Orazio, A., Grande, M., De Vittorio, M. (2023). Design and Fabrication of a Plastic-Free Antenna on a Sustainable Chitosan Substrate. *IEEE Electron Device Letters*, *44*(2), 341-344. https://doi.org/10.1109/LED.2022.3232986

Martinez Villadiego, K., Arias Tapia, M.J., Useche, J., Escobar Macías, D. (2022). Thermoplastic Starch (TPS)/Polylactic Acid (PLA) Blending Methodologies: A Review. *Journal of Polymers and the Environment*, *30*(1), 75-91. https://doi.org/10.1007/s10924-021-02207-1

Mittal, M., Ahuja, S., Yadav, A., Aggarwal, N.K. (2023). Development of poly(hydroxybutyrate) film incorporated with nano silica and clove essential oil intended for active packaging of brown bread. *International Journal of Biological Macromolecules*, *233*, 123512. https://doi.org/10.1016/j.ijbiomac.2023.123512

Morão, A., de Bie, F. (2019). Life Cycle Impact Assessment of Polylactic Acid (PLA) Produced from Sugarcane in Thailand. *Journal of Polymers and the Environment*, *27*(11), 2523-2539. https://doi.org/10.1007/s10924-019-01525-9

Mort, R., Peters, E., Curtzwiler, G., Jiang, S., Vorst, K. (2022). Biofillers Improved Compression Modulus of Extruded PLA Foams. *Sustainability*, *14*(9), 5521. https://doi.org/10.3390/su14095521

Murariu, M., Paint, Y., Murariu, O., Laoutid, F., Dubois, P. (2022). Tailoring and Long-Term Preservation of the Properties of PLA Composites with "Green" Plasticizers. *Polymers*, *14*(22), 4836. https://doi.org/10.3390/polym14224836

Najafidoust, A., Allahyari, S., Rahemi, N., Tasbihi, M. (2020). Uniform coating of TiO2 nanoparticles using biotemplates for photocatalytic wastewater treatment. *Ceramics International*, *46*(4), 4707–4719. https://doi.org/10.1016/j.ceramint.2019.10.202

Nakaji, Y., Tamura, M., Miyaoka, S., Kumagai, S., Tanji, M., Nakagawa, Y., … Tomishige, K. (2021). Low-temperature catalytic upgrading of waste polyolefinic plastics into liquid fuels and waxes. *Applied Catalysis B: Environmental*, *285*, 119805. https://doi.org/10.1016/j.apcatb.2020.119805

Nguyen, H.T., Sionkowska, A., Lewandowska, K., Brudzyńska, P., Szulc, M., Saha, N., … Saha, P. (2022). Chitosan Modified by Kombucha-Derived Bacterial Cellulose: Rheological Behavior and Properties of Convened Biopolymer Films. *Polymers*, *14*(21), 4572. https://doi.org/10.3390/polym14214572

Noivoil, N., Yoksan, R. (2021). Compatibility improvement of poly(lactic acid)/thermoplastic starch blown films using acetylated starch. *Journal of Applied Polymer Science*, *138*(2), 49675. https://doi.org/10.1002/app.49675

Otey, F.H. (1976). Current and Potential Uses of Starch Products in Plastics. *Polymer-Plastics Technology and Engineering*, *7*(2), 221-234. https://doi.org/10.1080/03602557608063115

Ou, Z., Zhou, Q., Rao, X., Yang, H., Huo, C., Du, X. (2021). Cellulose Isolated From Waste Rubber Wood and Its Application in PLA Based Composite Films. *Frontiers in Bioengineering and Biotechnology*, *9*. Retrieved from https://www.frontiersin.org/articles/10.3389/fbioe.2021.666399

Oyom, W., Zhang, Z., Bi, Y., Tahergorabi, R. (2022). Application of starch-based coatings incorporated with antimicrobial agents for preservation of fruits and vegetables: A review. *Progress in Organic Coatings*, *166*, 106800. https://doi.org/10.1016/j.porgcoat.2022.106800

Pal, K., Bharti, D., Sarkar, P., Anis, A., Kim, D., Chałas, R., … Jarzębski, M. (2021). Selected Applications of Chitosan Composites. *International Journal of Molecular Sciences*, *22*(20), 10968. https://doi.org/10.3390/ijms222010968

Pan, Z., Sheng, J., Qiu, C., Wei, H., Yang, Q., Pan, J., Li, J. (2022). A Magic Filter Filled with Waste Plastic Shavings, Loofah, and Iron Shavings for Wastewater Treatment. *Polymers*, *14*(7), 1410. https://doi.org/10.3390/polym14071410

Papari, S., Bamdad, H., Berruti, F. (2021). Pyrolytic Conversion of Plastic Waste to Value-Added Products and Fuels: A Review. *Materials*, *14*(10), 2586. https://doi.org/10.3390/ma14102586

Park, S., Oh, Y., Yun, J., Yoo, E., Jung, D., Oh, K.K., Lee, S. H. (2020). Cellulose/biopolymer/Fe3O4 hydrogel microbeads for dye and protein adsorption. *Cellulose*, *27*(5), 2757-2773. https://doi.org/10.1007/s10570-020-02974-5

Pazhamannil, R.V., V.N., J.N., P., G., Edacherian, A. (2022). Property enhancement approaches of fused filament fabrication technology: A review. *Polymer Engineering & Science*, *62*(5), 1356–1376. https://doi.org/10.1002/pen.25948

Perez-Nakai, A., Lerma-Canto, A., Dominguez-Candela, I., Ferri, J. M., Fombuena, V. (2023). Novel Epoxidized Brazil Nut Oil as a Promising Plasticizing Agent for PLA. *Polymers*, *15*(9), 1997. https://doi.org/10.3390/polym15091997

Popa, M.S., Frone, A.N., Panaitescu, D.M. (2022). Polyhydroxybutyrate blends: A solution for biodegradable packaging? *International Journal of Biological Macromolecules*, *207*, 263-277. https://doi.org/10.1016/j.ijbiomac.2022.02.185

Prata, J.C., Silva, A.L. P., Duarte, A.C., Rocha-Santos, T. (2021). The road to sustainable use and waste management of plastics in Portugal. *Frontiers of Environmental Science & Engineering*, *16*(1), 5. https://doi.org/10.1007/s11783-021-1439-x

Rajeshkumar, G., Arvindh Seshadri, S., Devnani, G.L., Sanjay, M.R., Siengchin, S., Prakash Maran, J., … Ronaldo Anuf, A. (2021). Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites – A comprehensive review. *Journal of Cleaner Production*, *310*, 127483. https://doi.org/10.1016/j.jclepro.2021.127483

Rana, A.K., Thakur, M.K., Saini, A.K., Mokhta, S.K., Moradi, O., Rydzkowski, T., … Thakur, V. K. (2022). Recent developments in microbial degradation of polypropylene: Integrated approaches towards a sustainable environment. *Science of The Total Environment*, *826*, 154056. https://doi.org/10.1016/j.scitotenv.2022.154056

Rangira, I., Gu, B.-J., Ek, P., Ganjyal, G.M. (2020). Pea starch exhibits good expansion characteristics under relatively lower temperatures during extrusion cooking. *Journal of Food Science*, *85*(10), 3333–3344. https://doi.org/10.1111/1750-3841.15450

Ray, S., Prajapati, V., Patel, K., Trivedi, U. (2016). Optimization and characterization of PHA from isolate Pannonibacter phragmitetus ERC8 using glycerol waste. *International Journal of Biological Macromolecules*, *86*, 741-749. https://doi.org/10.1016/j.ijbiomac.2016.02.002

Rezvani Ghomi, E., Khosravi, F., Saedi Ardahaei, A., Dai, Y., Neisiany, R. E., Foroughi, F., … Ramakrishna, S. (2021). The Life Cycle Assessment for Polylactic Acid (PLA) to Make It a Low-Carbon Material. *Polymers*, *13*(11), 1854. https://doi.org/10.3390/polym13111854

Rhu, D.H., Lee, W.H., Kim, J.Y., Choi, E. (2003). Polyhydroxyalkanoate (PHA) production from waste. *Water Science and Technology*, *48*(8), 221-228. https://doi.org/10.2166/wst.2003.0472

Richter, J.K., Pietrysiak, E., Ek, P., Dey, D., Gu, B.-J., Ikuse, M., … Ganjyal, G.M. (2022). Extrusion characteristics of ten novel quinoa breeding lines. *Journal of Food Science*, *87*(12), 5349-5362. https://doi.org/10.1111/1750-3841.16360

Rizal, S., Lai, T.K., Muksin, U., Olaiya, N.G., Abdullah, C.K., Ikramullah, … Abdul Khalil, H.P.S. (2020). Properties of Macroalgae Biopolymer Films Reinforcement with Polysaccharide Microfibre. *Polymers*, *12*(11), 2554. https://doi.org/10.3390/polym12112554

Rodriguez Llanos, J.H., Tadini, C.C., Gastaldi, E. (2021). New strategies to fabricate starch/chitosan-based composites by extrusion. *Journal of Food Engineering*, *290*, 110224. https://doi.org/10.1016/j.jfoodeng.2020.110224

Salmas, C.E., Giannakas, A.E., Baikousi, M., Leontiou, A., Siasou, Z., Karakassides, M.A. (2021a). Development of Poly(L-Lactic Acid)/Chitosan/Basil Oil Active Packaging Films via a Melt-Extrusion Process Using Novel Chitosan/Basil Oil Blends. *Processes*, *9*(1), 88. https://doi.org/10.3390/pr9010088

Salmas, C.E., Giannakas, A.E., Baikousi, M., Leontiou, A., Siasou, Z., Karakassides, M.A. (2021b). Development of Poly(L-Lactic Acid)/Chitosan/Basil Oil Active Packaging Films via a Melt-Extrusion Process Using Novel Chitosan/Basil Oil Blends. *Processes*, *9*(1), 88. https://doi.org/10.3390/pr9010088

Samadam, A., Vallepalli, R., Neeraj Kumar, K., Sreekanth, M., Raman Goud, R. (2022). Mechanical properties evaluation and behaviour of cellulose-HDPE composite. *Materials Today: Proceedings*, *62*, 3405-3410. https://doi.org/10.1016/j.matpr.2022.04.271

Samadhiya, K., Sangtani, R., Nogueira, R., Bala, K. (2022). Insightful Advancement and Opportunities for Microbial Bioplastic Production. *Frontiers in Microbiology*, *12*. Retrieved from https://www.frontiersin.org/articles/10.3389/fmicb.2021.674864

Samaniego, A.J., Espiritu, R. (2022). Prospects on utilization of biopolymer materials for ion exchange membranes in fuel cells. *Green Chemistry Letters and Reviews*, *15*(1), 253-275. https://doi.org/10.1080/17518253.2022.2040599

Scalera, F., Monteduro, A.G., Maruccio, G., Blasi, L., Gervaso, F., Mazzotta, E., … Piccirillo, C. (2021). Sustainable chitosan-based electrical responsive scaffolds for tissue engineering applications. *Sustainable Materials and Technologies*, *28*, e00260. https://doi.org/10.1016/j.susmat.2021.e00260

Shang, H., Xu, K., Li, X., Lu, S., Ke, L., Yang, H.-R., … Shen, B. (2022). UV-protective and high-transparency poly(lactic acid) biocomposites for ecofriendly packaging of perishable fruits. *International Journal of Biological Macromolecules*, *222*, 927-937. https://doi.org/10.1016/j.ijbiomac.2022.09.219

Siracusa, V., Blanco, I. (2020). Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. *Polymers*, *12*(8), 1641. https://doi.org/10.3390/polym12081641

Spiridon, I., Anghel, N.C., Darie-Nita, R.N., Iwańczuk, A., Ursu, R.G., Spiridon, I.A. (2020). New composites based on starch/Ecoflex®/biomass wastes: Mechanical, thermal, morphological and antimicrobial properties. *International Journal of Biological Macromolecules*, *156*, 1435-1444. https://doi.org/10.1016/j.ijbiomac.2019.11.185

Swetha, T.A., Bora, A., Mohanrasu, K., Balaji, P., Raja, R., Ponnuchamy, K., … Arun, A. (2023). A comprehensive review on polylactic acid (PLA) – Synthesis, processing and application in food packaging. *International Journal of Biological Macromolecules*, *234*, 123715. https://doi.org/10.1016/j.ijbiomac.2023.123715

Tábi, T., Ageyeva, T., Kovács, J.G. (2022). The influence of nucleating agents, plasticizers, and molding conditions on the properties of injection molded PLA products. *Materials Today Communications*, *32*, 103936. https://doi.org/10.1016/j.mtcomm.2022.103936

Wang, Y., Zhong, Y., Shi, Q., Guo, S. (2021). Study of the Preparation and Properties of TPS/PBSA/PLA Biodegradable Composites. *Journal of Composites Science*, *5*(2), 48. https://doi.org/10.3390/jcs5020048

Wang, Y.-J., Liu, W., Sun, Z. (2004). Effects of glycerol and PE-g-MA on morphology, thermal and tensile properties of LDPE and rice starch blends. *Journal of Applied Polymer Science*, *92*(1), 344-350. https://doi.org/10.1002/app.20015

Wróblewska-Krepsztul, J., Rydzkowski, T., Borowski, G., Szczypiński, M., Klepka, T., Thakur, V.K. (2018). Recent progress in biodegradable polymers and nanocomposite-based packaging materials for sustainable environment. *International Journal of Polymer Analysis and Characterization*, *23*(4), 383–395. https://doi.org/10.1080/1023666X.2018.1455382

Wu, J., Hu, T., Wang, H., Zong, M., Wu, H., Wen, P. (2022). Electrospinning of PLA Nanofibers: Recent Advances and Its Potential Application for Food Packaging. *Journal of Agricultural and Food Chemistry*, *70*(27), 8207-8221. https://doi.org/10.1021/acs.jafc.2c02611

Xue, C., Wilson, L.D. (2021). An Overview of the Design of Chitosan-Based Fiber Composite Materials. *Journal of Composites Science*, *5*(6), 160. https://doi.org/10.3390/jcs5060160

Yahya, E.B., Jummaat, F., Amirul, A.A., Adnan, A.S., Olaiya, N.G., Abdullah, C.K., … Khalil, H.P.S.A. (2020). A Review on Revolutionary Natural Biopolymer-Based Aerogels for Antibacterial Delivery. *Antibiotics*, *9*(10), 648. https://doi.org/10.3390/antibiotics9100648

Yang, S., Ma, H., Chen, Y., Sun, M., Liu, H., Zhou, X. (2023). Optimization of processing parameters in poly(lactic acid)-reinforced acetylated starch composite films by response surface methodology. *Iranian Polymer Journal*, *32*(3), 251-261. https://doi.org/10.1007/s13726-022-01113-0

Yu, T.-Y., Tseng, Y.-K., Lin, T.-H., Wang, T.-C., Tseng, Y.-H., Chang, Y.-H., … Su, W.-F. (2022). Effect of cellulose compositions and fabrication methods on mechanical properties of polyurethane-cellulose composites. *Carbohydrate Polymers*, *291*, 119549. https://doi.org/10.1016/j.carbpol.2022.119549

Zhang, Y., Xu, X. (2022). Predicting mechanical performance of starch-based foam materials. *Journal of Cellular Plastics*, *58*(3), 505-514. https://doi.org/10.1177/0021955X211062638

Zhao, X., Liu, J., Li, J., Liang, X., Zhou, W., Peng, S. (2022). Strategies and techniques for improving heat resistance and mechanical performances of poly(lactic acid) (PLA) biodegradable materials. *International Journal of Biological Macromolecules*, *218*, 115-134. https://doi.org/10.1016/j.ijbiomac.2022.07.091

Zhou, C., Wu, M., Sun, D., Wei, W., Yu, H., Zhang, T. (2022). Twin-Screw Extrusion of Oat: Evolutions of Rheological Behavior, Thermal Properties and Structures of Extruded Oat in Different Extrusion Zones. *Foods*, *11*(15), 2206. https://doi.org/10.3390/foods11152206

Zhou, L., Ke, K., Yang, M.-B., Yang, W. (2021). Recent progress on chemical modification of cellulose for high mechanical-performance Poly(lactic acid)/Cellulose composite: A review. *Composites Communications*, *23*, 100548. https://doi.org/10.1016/j.coco.2020.100548

Zubair, M., Ferrari, R., Alagha, O., Mu'azu, N. D., Blaisi, N. I., Ateeq, I. S., Manzar, M. S. (2020). Microwave Foaming of Materials: An Emerging Field. *Polymers*, *12*(11), 2477. https://doi.org/10.3390/polym12112477