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ENVIRONMENTAL AND HEALTH IMPACTS OF BIOBASED POLYMERS

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Abstract

The use of biopolymers is predicted to grow in the coming years as the world searches for solutions to its sustainability problems. Pursuing biobased materials is widely thought of as the sustainable response to moving away from petroleum-based materials and the plastic-waste issue; however, its potential environmental and human health impacts are being questioned. Notably, the controversies related to biopolymers' renewable feedstocks include adding pressure to the food economy, land use, occupational hazards, and environmental pollution with potential human exposure and adverse health effects. Other resource burdens include energy and water. Many biopolymers are designed to biodegrade, compost, or be recycled to help reduce plastic waste. However, infrastructure is overall insufficient and cannot support these end-of-life pathways. The article's primary purpose is to discuss these large pieces of the sustainability narrative and their environmental and health impact. Poly(lactic) acid is used as a case study to generate a multi-faceted understanding of the greater system in a 'real-life' context. Finally, recommendations for future strategies to increase the sustainability and safety of biopolymers are provided.

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Introduction

Society has become dependent on polymers and plastics throughout all areas of life. Plastic polymers are man-engineered synthetic organic macromolecular chains used for manufacturing plastics, synthetic fibers, foams, coating, adhesives, and sealants.[1] Additives added to plastic polymers enable various applications by supplying, enhancing, and prolonging desirable characteristics for different end products.[2] Additives include stabilizers, flame retardants, pigments, and fillers.[1] The versatility of properties, chemical composition, and applications has made plastics integral to society's function over the last century.

Petrochemical-based polymers and additives make up most plastics manufactured today. Deriving polymers, plastic and additives from non-renewable fossil fuels is not sustainable and pose human health and environmental risk.[1]. Plastic deterioration threatens to leach into the soil, air, water, and food throughout extraction, product life, and end-of-life.[2] These plastics are highly persistent and burden marine and terrestrial environments globally. The increasing demand for plastic materials comes with a growing material waste issue. In typical conditions, it requires hundreds of years for polymers to degrade.[3] Plastic solid waste is manufactured on a massive scale globally. More than 300 million metric tons per year are created globally with low levels of recycling and reuse.[4]

The growing concern regarding the harmful impacts of plastics has led to multi-government action restricting many single-use plastics and improving plastics' waste management strategies.[5] As the demand for plastics increases globally, plastics based on renewable feedstocks are being innovated. Alternatives are possible for almost every conventional plastic material and function.[5] Bioplastics are plastic materials manufactured from renewable biomass sources, including sugar cane, corn starch, vegetable oil, and microorganisms.[6] Bioplastics produce significantly less greenhouse gas emissions than traditional plastics and lessen dependency on fossil fuels as a feedstock.[3] They are also carbon neutral since plant biomass absorbs an equivalent mass of carbon dioxide as it emits during degradation.[3]

However, while biopolymers may adhere to green design more than petroleum-derived polymers, they still have major adverse environmental and human health impacts. Biopolymers need large-scale land use, and feedstock production resulting in high pollution due to the fertilizers and pesticides used in farming crops and chemical processing.[3] The end-of-life disposal of bioplastics is too complicated for current waste management systems in most regions. Although the feedstock is renewable, the end-product is still plastic. Some are biodegradable, and others are not.[5] If it is biodegradable, it requires a particular environment to break down. Commonly, bioplastics are sent to a landfill and deprived of those appropriate conditions, resulting in high methane emissions from degradation or no degradation over 100 years. Bioplastics to be recycled need to be separate from other batches of recycled plastics or risk contaminating them which is currently difficult for many facilities.[3]

The design flaws of bioplastics throughout its products, feedstocks, a manufacturing process are repairable in future iterations. The principles of green chemistry and green engineering need to be applied during the design stage of polymers to address emissions, energy, waste, and all other harmful impacts of plastics. Chemists can design bioplastics to reduce or eliminate physical, global, and toxicological risks.[7] However, if the conditions required do not match the system, then it's a failure. Systems need to be taken into consideration to determine solutions that do not shift burdens or become regrettable.[8] If a biopolymer requires light, water, oxygen, and temperature to degrade but ends in a landfill, it may not degrade because of the lack of these elements.[6] This example shows the importance of both the chemistry and the system being designed in consideration of each other.

Methodology

The present work is an attempt to give a generic overview on environmental, social, and health impacts that are associated with biopolymers from its raw material extraction to its end of life. Specifically, it examines how PLA exists within its current circumstances and infrastructure to as a case example. PLA was chosen because of its wide applicability, large market share, and abundance of research literature available. This is neither a systematic nor a comprehensive review. The data collection process involved research scientific literature and general commercial literature, paying close attention to life cycle analysis, and using theoretical and empirical articles.

a) Summarize resources required for material extraction and processing and discuss the greater impact on the environmental and human health
b) Briefly outline characteristics, properties, key functions, and behavior of PLA.

c) Evaluate how PLA, as the most used and researched biopolymer, impacts the environment and human health.

Discussion

System Overview

Feedstock

Feedstocks for biopolymers are categorized into three generations: first, second, and third. The first-generation feedstocks are typically carbohydrate-rich and can be used as food by humans and animals.[9] First-generation feedstocks include corn, sugarcane, wheat, potato, sugar beet, rice, and plant oil.[10] These were the first feedstocks for biobased polymers and have developed a significant technical maturity. The downside of first-generation feedstocks is the required intensive agriculture and the potential competition with food and animal feed versus fuel.[11] Both concerns negatively impact human health and the environment. These adverse impacts led to the development of alternative feedstocks with less intense dedicated land use.

The second-generation feedstock groups together feedstocks that are not used for food or animal feed. Examples of second-generation feedstocks include non-food crops (e.g., cellulose) or by-products from the first generation feedstocks such as corn stover or sugarcane bagasse.[9] Second-generation feedstocks do not pose a direct conflict with food unless it is residue from the first-generation. Additionally, the continued concern of “food versus fuel” should consider if the non-food crops are harvested on food production land.[11] Although agricultural wastes are generally inexpensive; there are relatively high costs associated with processing these feedstocks.[12]

The third generation of feedstocks includes biomass derived from algae or industrial or municipal waste.[9] This generation is at the earliest stage of innovation and development, which translates to less research on human health and environmental impact. However, this biomass does not require fertilizers, pesticides, herbicides, or land. The downside of third-generation feedstocks is the current cost to grow and process the feedstocks into the product.

Table 1: Overview on feedstock generations[13]

First Generation	Second Generation	Third Generation
• Corn • Wheat • Sugarcane • Potato • Sugar beet • Plant oil	• Corn stover • Cellulose • Wood • Switchgrass • Wheat straw	• Municipal waste • Industrial waste • Biomass from algae • Food industry by-product

Feedstock Implications

Overall, life cycle analyses have found that biobased plastics of the first generations have less severe significant adverse human health and environmental impact than their petrochemical counterparts.[14] However, this is not true for every category. The high requirement of water and arable land during the feedstock growth phase is more intensive than petrochemical materials.[15–17] The land use change from a natural environment to biomass agriculture comes with associated impacts on the environment. Converting natural spaces to agriculture is driving biodiversity loss, as native plants and animals are displaced/or have less area to habituate.[15,17,18]

The usage of pesticides and fertilizers during the growth part of the feedstock is frequently observed as the predominant source of concern for human health and the environment. Pesticide exposure routes are via inhalation, oral, and dermal routes from the air, waterway, or soil contamination and are linked to harmful algal blooms that create toxins and compounds in water that are dangerous to humans.[19] Exposure's adverse health impact includes respiratory problems, neurological effects, stomach or liver illness, and skin irritation. In addition, up to agrochemicals, 95 percent of applied micronutrients and 99 percent of used pesticides bounce off the plant and are wasted.[20] Eutrophication and acidification effects of first-generation feedstocks are also typically worse than their fossil fuel counterparts due to the production and usage of fertilizers.[15] Nutrients of the fertilizers can enter bodies of water causing eutrophication, and the emissions into the soil contribute to the acidification effect of biopolymers.[19] Specifically, the utilization of nitrogen fertilizers adds to the global warming impact even when taking the net CO_2 effect from plant growth into consideration, accounting for the CO_2 release at the end of the product's life.[19]

The food vs. fuel debate is critical because first-generation feedstocks are also used as food, which translates to biopolymer production being in direct competition with food production.[18] A negative economic impact could be that higher demand for corn and sugar for bioplastic production could cause an increase in food prices, contributing to food insecurity. Food security is cited as one of the most significant public health impacts of the food vs. fuel issues.[18] The competition for arable land between food and feed and industrial production is presently minimal. Currently, less than 0.02 percent of the world's agricultural areas are used for bioplastic feedstock cultivation.[20] With the estimated increased growth in the bioplastic market, the agricultural area, is predicted to still be a low <0.06 percent in 2025.[20] For context, the agricultural area used for pasture, food, and feed is about 91 percent.[20] However, even if competition between food and feed and biopolymer feedstock cultivation is low, rising food demands and existing pressures on food do exist. They will impact the resources available for industrial production.

Water

Significant water is used to cultivate and process bio-based feedstocks to manufacture plastics. Feedstocks that are the result of industrial agriculture can result in the contamination of water. Both realities of current biopolymers add pressure to water resources available. Many biobased plastics are not designed to break down in water and are littering seawater.[16]

End-of-life

Recycling biobased plastics is observed to have the most benefits for the environment. Biopolymers can be integrated into existing recycling and recovery waste streams depending on the material and application.[21] If a specific plastic/bioplastic already has an existing recycling stream, the bioplastic can be recycled together with its conventional counterparts. For example, biobased PET can be recycled in the same stream as conventional PET. Biopolymers offer biodegradation and energy recovery if given the correct, controlled environment.[12] Composting is typically an aerobic process (with oxygen). In some cases composted biopolymers do not benefit compost quality or enable energy recovery.[21] Not all biopolymers are biodegradable or compostable and will be recycled, landfilled, or incinerated.[9] According to several studies, composting may have a few advantages over incineration with heat recovery in municipal solid waste incinerators.[21] Composting can result in few valuable by-products and energy.[21] Composting and municipal incineration have similar CO_2 releases. Landfilling is the least recommended pathway, although biobased plastics will not generate toxic emissions if they do not break down.[9] The lack of moisture and oxygen and inconsistent temperatures inhibit the degradation of biopolymers in a landfill environment.[9]

Many governments and municipalities have not implemented the necessary infrastructure to recycle biobased plastic.[22] Biodegradable and compostable polymers are designed to breakdown when exposed to certain environmental elements. A biopolymer like PLA, will not break down in a landfill environment.[9] This means added pressure on landfills and requires more land for waste. This is counter to one of the drivers of biopolymer innovation, to reduce physical waste and dependency on landfills. Another concern are additives and biodegradable microplastics formed when biodegradable plastics enter the environment.[22,23] Potentially toxic additives and microplastics can be released from bioplastic products at any time during its life span, and may also be released during various recycling methods.[23] More research is needed to make conclusions about the environmental and health burdens due to the fate and migration of biobased microplastics.[22] Recycling has the potential to close the carbon cycle and contribute to a circular economy. Generating valuable byproducts from biobased materials should be a priority to reduce raw materials needed and EOL waste.

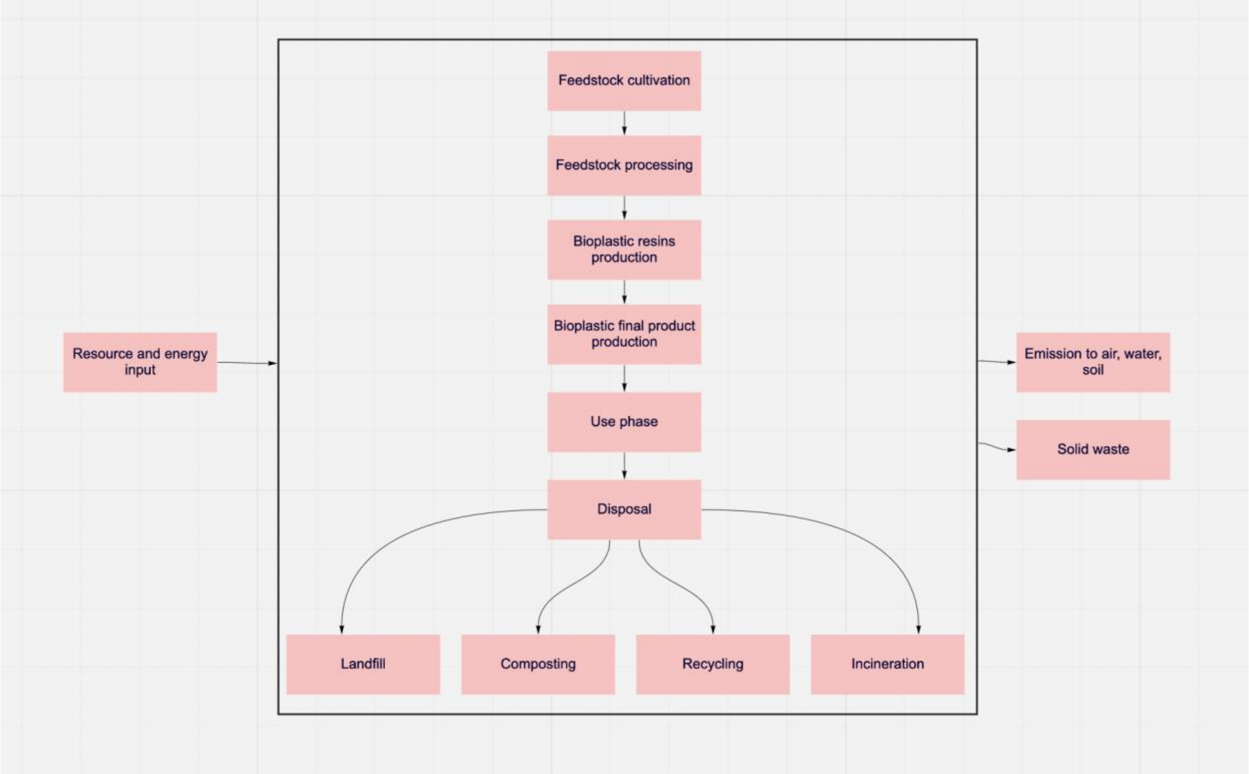

Figure 1 Biopolymer flow diagram

Poly(lactic) Acid Case Study

PLA is an aliphatic biobased and biodegradable biopolymer used for various applications including, packaging, medical devices, and other rigid and flexible durable products.[9] The biopolymer is made of lactic acid molecules, the most widely available raw material found in nature. PLA made up about 19 percent of global production capacities of all bioplastics in 2021.[24] PLA dominates the other biopolymer alternatives in packaging as the most common bioplastic used. In 2019, the production volume of PLA was about 290 thousand tons.[24] PLA production will continue to increase steadily around the world. The market is driven by increased consumer interest in environmentally friendly plastics and the increasing governmental regulations and bans against single-use and other plastic items. Lactic acid can be created via the chemical synthesis of microbial fermentation processes.[25] The primary feedstock used for PLA is sugar and starch. As a thermoplastic polyester, it softens when heat is applied and is rigid when cool, and can do so many times without changing its mechanical and chemical properties.[26] PLA is presently considered to have enormous potential for commercial use and possesses improved durability, transparency, and mechanical strength to compete with traditional petroleum-based plastic.[9] PLA material is relatively cheap and has positive mechanical properties, processability, renewability, and non-toxicity.[27,9]

Polymer characterization can vary depending on the degree of polymerization of the molecule and any bonding with reactants.[9] To account for the variation, and because polymers emphasize the characteristics of their monomer unit, the monomer unit is sometimes discussed. Polymers tend to exhibit a high molecular weight, restricting transport across biological membranes. High molecular weight can suggest a low risk posed to human health of the environment through absorption. Molecular weight also impacts the physical, chemical, and mechanical properties of how a polymer behaves under certain conditions.

Depending on its manufacturing process, the crystallinity and, therefore, properties of PLA, can vary widely. The monomer unit of PLA, lactic acid, has chiral carbon and can be either the D- or L- isomer.[28] The content of L- and D-enantiomers in the polyester chain about synthesis translates to its optical purity, which strongly impacts overall properties. The factors during synthesis include the residence time, catalyst type, consternation, temperature, and the sequence and ratio of L- and D-lactic acid units in the final polymer.[29] PLA containing higher than 93% of the L-lactic is considered semi-crystalline. PLA with lower optical purity: PLA with

50–93% L-lactic is considered amorphous.[9] PLA can range from low to high molecular weight. Low or medium molecular weight of PLA is not exceeding 20,000-50,000 g/mol, and the high molecular weight reaches from 80,000 to 250,000 g/mol.[29] The polymerization process makes PLA inert, decreasing potential health and environmental problems. However, the lack of reactive side-chain groups makes it difficult to modify.[30]

Macroscopic properties are of high interest as they can also be a potential hazard to human health and the environment and provide a key function that makes the polymer attractive. The glass transition temperature (T_g) influences physical characteristics, including density, heat capacity, and mechanical and rheological properties, and is a significant parament for PLA since substantial changes in polymer chain mobility occur at and above Tg (45-60 C).[30,31] Both T_g and melting temperature (T_m) are significant physical parameters for predicting behaviors for semicrystalline PLA.[30] Molar mass, thermal history, and purity of the polymer strongly impact T_m and degree of crystallinity.[30] The density of amorphous and crystalline PLA has been reported as 1.248 g/ml and 1.290 g/ml, respectively. The density of solid PLA was reported as 1.36 g/cm^3 for L-lactide, 1.33 g/cm3 for meso-lactide, 1.36 g/cm^3 and 1.25 g/cm^3 for crystalline and amorphous PLA, respectively.[30]

Table 2 Physical properties of PLA

Molecular weight (g/mol)	66,000
Polymer density (g/cm^3)	1.21-1.25
Tensile strength (MPa)	21-60
Glass transition temperature (°C)	45-60
Melting temperature (°C)	150-162

Durability is a key function a biopolymer needs to attain to become an alternative for conventional polymers in many applications. However, biopolymers should not be persistent past their use phase to improve upon the conventional polymer. Generally, PLA is soluble in dioxane, acetonitrile, chloroform, methylene chloride, 1,1,2-trichloroethane, and dichloroacetic acid. PLA will dissolve in ethylbenzene, toluene, acetone, and tetrahydrofuran at boiling temperatures and partially dissolve in these solvents at cold temperatures. PLA is not soluble in water, alcohols such as methanol, ethanol, propylene glycol, and unsubstituted hydrocarbons (e.g., hexane and heptane). Crystalline PLA is not soluble in acetone, ethyl acetate, or tetrahydrofuran.[30]

Polymer reactivity with water and catalysts determines the degradation rate of polymers.[30] PLA degrades primarily from exposure to moisture over several months. However, PLA can also be degraded by thermal- and photo-degradation.[32] The two stages of lactic acid-based polymer degradation are 1. Random non-enzymatic chain scission of the ester groups causes depletion of molecular weight 2. The molecular weight is lessened until the lactic acid and microorganisms naturally metabolize low molecular weight oligomers to yield carbon dioxide and water.[30] Particle size and shape, temperature, moisture, crystallinity, % isomer, residual lactic acid concentration, Mw, water diffusion, and metal impurities from the catalyst affect the reactivity and accessibility, which translates to impact on the polymer degradation rate.[30]

Additives are another important feature to consider because of their various impacts on the behavior of polymers and their potential human health and environmental risks. Additives can enhance polymer properties, such as flexibility, durability, and permeability.[23] Specific classes of additives can change the rate of PLA hydrolysis and degradation and other polymer properties. Additives are released from a product throughout all stages of its life cycle and are the source of toxic exposure to humans and the environment.[23] Potentially toxic additives contaminate soil, air, water, and food.[23] The leaching of toxic additives and consequently contaminated groundwater and soil is a concern for the polymers that break down in landfills.

Synthesis

The synthesis for PLA can be achieved by following three steps: 1. production of LA 2. purification of LA and lactide preparation 3. polycondensation of LA or Ring-Opening Polymerization (ROP) of lactides.[9] Although polycondensation is the most cost-effective method, creating a solvent-free PLA with high molecular weight is difficult. Chain extenders can increase biopolymers' molecular weight in a rapid reaction using polycondensation.[9] The downfall of this approach is a high amount of catalyst impurities as a product of the high levels necessary for acceptable reaction rates. Residual catalysts can result in catalyst toxicity, undesirable degradation, and uncontrolled hydrolysis rates.[23] This problem can be controlled by adding phosphoric or pyrophosphoric acid to deactivate the catalyst, and other strong acids like sulfuric acid can be used to precipitate and filter the catalyst. ROP is generally used to produce high molecular weight PLA. ROP follows three primary steps: 1. Polycondensation 2. Depolymerization 3. ROP.[29] This approach requires an additional purification step which is comparatively expensive and complex. Catalysts include transition metals like lead, zinc, yttrium, bismuth, and aluminum.[9] PLA is chemically synthesized by heavy metal catalysts, which is a concern in biomedical and food applications. Trace residues of heavy metal catalysts can be harmful to human health and finding a safe and environmentally friendly alternative should be a priority. It's common for manufacturers to enhance PLA properties with additive loading.[2]

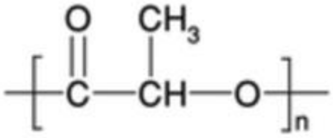

Figure 2 Chemical structure of PLA

Implications of Synthesis

The use of sulfuric acid is an occupational concern because of its highly corrosive properties. Heavy metal catalysts are also a concern during production and while the product is in use due residual exposure.[33] 1-Octanol is employed in the ring opening catalysis step to control molecular weight and accelerate the reaction.[29] This substance is a volatile and combustible liquid that can be absorbed into the body by contact, inhalation, and by ingestion causing irritation to the tissues.[34] 1-Octanol is slightly toxic to marine life and very high confidence for systemic toxicity following a single exposure.[35] The uses heavy metals and 1-octanol during lactic acid polymerization causing concern during disposal because it can build up on aquatic organisms and plants and has been found in human tissue due to its lipophilic properties.[9,23,34] Phosphoric or pyrophosphoric acid is also hazardous, causing sever skin burns and eye damage from unsafe exposure.[36] It has met Safer Choice Criteria for its function according to the US Environmental Protection Agency, it is still a chemical that should be considered for safer chemistry innovation.[36]

Energy

Compared to conventional polymers, PLA requires 65 percent less energy and emits 68 percent few greenhouse gases during its production stage.[29] For PLA, most of the energy consumption occurs during polymer production, while the agricultural practices to cultivate the raw materials consumed relatively little energy.[21] Anaerobic fermentation requires minimal energy, while aerobic fermentation requires significantly high energy costs due to slow growth and production rates.[21] High energy intensity is a barrier to innovative alternative feedstock in lactic acid production, such as liquid organic waste and microalgae.[25] The production of bioplastics is still dependent on fossil fuels as the source of energy.

End-of-life (EOL)

The four common paths for a PLA product at end-of-use are landfill, composting, recycling, and incineration.[26] PLA is relatively environmentally-friendly depending on the EOL scenario. PLA can degrade via hydrolysis, thermal degradation, and photodegradation, specifically from sunlight exposure. However, hydrolysis is the more common scenario. PLA needs to be exposed to water and high temperatures for an extended period to start the hydrolysis reactions responsible for degradation.[9] Landfill produce environmental impacts on the waste management options.[21] Since these circumstances are typically unavailable in landfills, PLA would degrade by one percent over 100 years in landfills.[21] Another study looking at PLA sheets observed major fragmentation occurred around 15 months.[9] Landfilling has the highest environmental impact of these four paths due to the delay in CO_2 and methane emissions beyond the first 100 years. PLA can also be incinerated, resulting in 19.5 MJ/kg (8,368 btu/lb) of energy and leaving no residue.[32]

Industrial composting facilities degrade PLA by chemical hydrolysis and then microbial digestion.[32] Composting is not the best EOL pathway because of its environmental impacts, which do not considerably improve the compost quality and do not allow for energy recovery. PLA can biodegrade in composts because of the nutrients contained in biowastes; PLA itself lacks enough nutrients to start the biodegradation process.[21] PLA sheets were observed to degrade entirely in 30 days under composting plant conditions.[9] PLA does not improve soil structure, nutrient retention, erosion and runoff reductions, or herbicide and water requirements reduction, as conventional inputs to composts facilities would.[21] However, composting PLA products would lessen pressure on landfills and contribute to landfill reduction goals.

Although PLA's recycling technology is still being researched for implementation, it shows promise to achieve environmental benefits and be the most favorable waste stream. Recycling a biobased polymer would increase the advantage of using renewable resources because it would lead to less use of agricultural land, fertilizers, and pesticides, which causes harm to human health and the quality of the environment.[37] The replacement of virgin PLA with recycled PLA translates to increased savings of greenhouse gas emissions and overall global warming impacts. Different recycling technologies for post-industrial and post-consumer PLA waste include mechanical, solvent-based, and chemical recycling. The challenges of recycling

PLA are that the infrastructure is not mature. Collected PLA must not have started degradation because it cannot be recycled or mixed with neat PLA as it can damage the quality of the neat polymer. Non-PLA materials also can never be mixed with recycled PLA resin because of the incompatibility of polymer components. Additives such as impact modifiers, reinforcing agents, and fillers may have an unpleasant effect on the recycled PLA and needs to go through compatibility testing before the start of the recycling process.[9]

Conclusion

Notably, all the solutions presented here are inextricably interconnected and are influenced by various internal and external factors. Each suggestion includes a balance of trade-offs, currently, there is no clear optimal environmentally and health-friendly pathway insight. Ultimately, many scenarios will need to be combined and pursued. More research, technology development, infrastructure, and logistics are necessary to innovate the ideal pathway. As biopolymers are further developed, future studies need to conduct thorough life cycle analyses to confirm environmental and health benefits.

Recommendations

Decouple PLA from agriculture

The most sustainable pathway for PLA and biopolymer production, in general, is to decouple PLA production from agricultural use completely. Literature has focused on utilizing by-products and waste streams; however, information regarding environmental performance is still limited. Organic waste would contribute to a circular economy, a significant future aspect of a sustainable economy. It would avoid the resource strain for land use, water use, toxic chemicals during cultivation, fertilizer input, and emission impacts from the cultivation process of first-generation feedstocks. Since third-generation feedstocks integrate their carbon into the polymers, its CO2 emission release into the atmosphere is at minimum latent for an extended period. Overall, it would reduce impacts on global environmental categories related to climate change, local ecological damages, and human health. This generation's clear disadvantages include its technological maturity and energy-intensive needs.

Sustainable agriculture

When pursuing first- and second-generation feedstocks, sustainable agriculture needs to be integrated responsibly to limit environmental and health category impacts. Although global land usage for bioplastics is relatively small, it's essential to use the land productively. The biomass type for a biopolymer should be chosen based on the sustainability and efficiency of the feedstock. Currently, the first generation of biomass is the most efficient feedstock due to its small amount of land to grow and high yields. Producers should focus on high-yielding crops to limit the environmental and health of intensive agricultural impacts due to their very high land efficacy. Specifically, sugar crops have the highest land efficiency, high GHG reductions, the lowest GHG abatement costs, and mature infrastructure. They are followed by starch crops which are less land efficient, with smaller GHG reductions but higher GHG abatement costs and similarly developed infrastructure.

Limit pesticides, herbicides, and fertilizers

Reducing and managing pesticides and fertilizers needs to be a priority because of their far-reaching impacts on public health and the environment. Preventing soil, water, and air pollution can be done by innovating better tools, designing chemically improved products, and changing the methods chemicals are used. Each approach is important to develop because of unequal access to any solution. Two approaches to chemically designing more efficient pesticides include 1. Making the droplets “less bouncy”[38] and 2. Delivering nanoparticles into plant leaves for direct travel to root.[39] Crops can also be genetically modified to create crops with a higher yield, higher resistance to pesticides and herbicides and to drought. This approach’s categorial impacts are still under research, however it can result in a higher output of product for a lesser input of resources, and less waste.

Recycling infrastructure

Recycling and composting streams for PLA, and other biobased plastics rising in popularity, need to be established to get the most benefit from using biobased plastics. Whether through governments and municipalities or private-public partnerships, bioplastics need to be efficiently separated from conventional plastics and be conveniently transported to commercial recycling and composting facilities.

Consumer-end waste management

Consumers need to understand the basics of material lifecycles and be educated on reusing materials and alternative, more sustainable materials. Reusing materials and using more sustainable substitute materials where possible will reduce raw material extraction, waste generation, and their potential impacts.

Field testing

Biopolymers may be designed for specific functionality, like biodegradation, but are only tested in a controlled setting. By not testing the biopolymers' behavior in the natural environment, external factors may impede the intended design. Many studies have shown that biodegradation tests executed in artificial environmental lack transferability to natural conditions. Field testing should be included to ensure the biopolymer achieves its intended performance.

Design polymers that can be recycled in existing system

Another solution to the end of life is to design the polymers to work within the existing system. To break down the polymers at the consumers' endpoint or be recycled with conventional plastics without additional separating processes. This can be managed through recycling or composting at home or degradation in natural environments. To achieve a successful polymer design, the system boundaries in which the chemical will exist should be integrated into the design process.

Green catalyst

Determining an environmentally friendly, non-toxic catalyst for reactions should be a priority. Homogenous and heterogeneous catalytic reactions are more energy and resource-efficient. They can also reduce unwanted byproducts and efficiently increase the reaction time. Specifically, it’s essential for biopolymers used for food packaging not to have residual byproducts from a toxic metal. Chemists have already implemented green catalysts using organic, organometallic, inorganic, and biological catalysts to eliminate the need for metal catalysts and their downsides.

Safe additives, or obsolete additives

Safer additives, copolymers, and other chemicals that will not migrate from the material and achieve the required performance should be used. Another idea for research and development is to design the biopolymer to perform all necessary functions and avoid the need for additives. Methods of green chemistry and design for the environment will be crucial.

Reduce occupational exposure

More research and development in alternatives are necessary for sulfuric acid, phosphoric acid, and heavy metal catalysts in PLA production to increase occupational safety. Additionally, safety measures to minimize the risk of fire hazards in manufacturing plants should be implemented. Avoid carcinogens, mutagens, and reproductive toxicants wherever possible in the system.

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