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RCMOS – Multidisciplinary Scientific Journal The Knowledge.
ISSN: 2675-9128. São Paulo-SP.

Year VII, v.1 2026 | Submission: April 22, 2026 | Accepted: April 25, 2026 | Publication: April 28, 2026

Ecodesign, Biodegradable Polymers and Circular Economy in Industrial Manufacturing: A Modification of Biopolymers for Reducing Corporate Carbon Footprint

Ecodesign, Biodegradable Polymers, and Circular Economy in Industrial Manufacturing: Modifying Biopolymers to Reduce Corporate Carbon Footprint

Ecodesign, biodegradable polymers and circular economy in industrial manufacturing: modifying biopolymers to reduce corporate carbon dioxide

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Summary

This article investigates the role of ecodesign, sustainable materials science, and the principles of the circular economy in the innovation and manufacturing of industrial products. It begins with a theoretical and experimental analysis of the modification of renewable biopolymers, such as poly(lactic acid) (PLA), through the incorporation of plasticizers and additives of plant origin (such as *Ricinus communis* L. oil), the study analyzes the changes in the thermal and mechanical properties and the biodegradability rate of the material under natural soil conditions. The application of these additivated biopolymers in the development of commercial packaging and products with controlled shelf life is discussed, evaluating the impact of replacing fossil-based plastics on achieving Environmental, Social and Corporate Governance (ESG) goals.
Keywords: Ecodesign. Biodegradable polymers. Poly(lactic acid). Circular economy. Industrial sustainability.

Abstract

This article investigates the role of ecodesign, sustainable materials science, and circular economy principles in the innovation and manufacturing of industrial products. Drawing upon theoretical and experimental analysis of renewable biopolymer modification, specifically Poly(lactic acid) (PLA) blended with bio-based plasticizers and additives (such as *Ricinus communis* L. oil), the study analyzed alterations in thermal, mechanical, and soil biodegradation properties under natural conditions. It discusses the application of these modified biopolymers in commercial packaging and controlled-lifespan products, evaluating the impact of replacing fossil-based plastics to achieve corporate Environmental, Social, and Governance (ESG) goals.
Keywords: Ecodesign. Biodegradable polymers. Poly (lactic acid). Circular economy. Industrial sustainability.

Introduction

The environmental crisis resulting from the accumulation of plastic waste of fossil origin and the urgency in Mitigating climate change requires a profound restructuring of systems. production and consumption of global industry. As postulated by McDonough and Braungart (2002) In the *Cradle to Cradle* model , industrial materials must be designed to continuously re-enter the production cycle as technical nutrients or to be absorbed. by nature in a safe way as biological nutrients, eliminating the very concept of waste. In this paradigm, ecodesign guides the development of products whose life cycle...

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Life is planned from the selection of raw materials to its final disposal.
The search for viable substitutes for conventional petroleum-derived polymers has driven...
the use of poly(lactic acid) (PLA), a biodegradable thermoplastic polyester and
Compostable material obtained from renewable sources, such as corn starch or sugarcane.
However, in its pure form, PLA presents significant technical limitations for applications.
Industrial and commercialization of flexible products, such as those with high fragility and low
elongation at break and slow rate of degradation under natural soil conditions without
Industrial composting.
This article proposes a reflection on the chemical and structural modification of PLA through...
addition of plasticizers of vegetable origin, specifically castor oil *(Ricinus)*
communis L.), for the development of new biodegradable polymeric materials.
Anchoring itself in the theories of materials science, ecodesign, and circular economy, the study
analyzes how adjusting the rheological and thermal properties of the biopolymer allows for
manufacturing packaging and utility items that combine high commercial performance and
Rapid biodegradability and environmental impact.

Methodology

This study adopts a mixed methodological approach, based on a literature review of
Polymer science and descriptive analysis of processing and characterization processes.
of polymeric biocompounds. The research is based on the academic literature of
specialization in biodegradable materials and ecodesign, based on formulations of
Bastioli (2005), Manrich (2006) and Cerdà and Lofthouse (2002).
The analysis examines the processes of incorporation of *Ricinus communis* L. oil into the matrix of
PLA is produced using single-screw and twin-screw extrusion followed by body molding.
test. Thermal properties are evaluated using Scanning Calorimetry.
Digital scanning electron microscopy (DSC), glass transition temperature *(Tg),* melting temperature *(Tm),* as well as the
Mechanical behavior under tensile tests. Monitoring the rate of
Biodegradability is analyzed using the mass loss method upon direct exposure in soil.
natural at controlled time intervals.
Analytical triangulation counteracts the technical requirements demanded for packaging for use.
commercial considerations relate to the environmental degradation profile of biopolymers with additives. This approach
The methodological approach allows for the scientific substantiation of the thesis that the use of additives
Renewable materials in bioplastic matrices increase the material's mechanical flexibility and accelerate their...

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assimilation into the environment, offering the productive sector real alternatives to plastics.
Non-renewable.

Chapter 1: Principles of Ecodesign, Life Cycle Analysis, and Circular Economy

Ecodesign establishes the systematic integration of environmental aspects into design and
product development, aiming to reduce its ecological impact throughout its entire lifecycle.
life cycle without compromising its commercial functions and usability. According to Cerdà and
Lofthouse (2002), ecodesign requires the designer to consider the extraction of raw materials, the
energy consumption in manufacturing, efficiency in transportation, and post-consumer disposal before
that the product enters the industrial production line.
Life Cycle Assessment (LCA) is the scientific tool used to quantify the flows
of matter and energy associated with a product, from cradle to grave *or* from the cradle
Cradle *to cradle.* The application of LCA reveals that most impacts
The environmental impact of a consumer good is determined during the initial design phase. The decision
to replace a synthetic polymer of fossil origin with a biodegradable matrix obtained from
Renewable biomass drastically reduces the accumulated carbon footprint in the raw material phase.
cousin.
The transition from the traditional linear economy to the circular economy model requires the creation of
of products whose material components can be easily separated, recycled or
biologically decomposed. As summarized by Bastioli (2005), bioplastics
They play a central role in the circular economy for short-life applications, such as
such as food packaging and commercial disposable items, where contamination by
Organic waste makes traditional mechanical recycling unfeasible.
In addition to environmental benefits, the adoption of ecodesign and bioplastics strategies responds
due to increasing regulatory demands and corporate guidelines on Environmental Governance,
Social and Corporate Governance (ESG). Companies that incorporate renewable and recyclable materials into
Their products and commercial facilities enhance their brand value and reduce environmental liabilities.
and they meet the demands of conscious consumers.

It can be concluded that ecodesign is the fundamental discipline for industrial sustainability in
21st century. By designing products with renewable materials and planned life cycles, the
The industry eliminates waste, reduces greenhouse gas emissions, and consolidates a model.
economic development compatible with the planet's ecological limits.

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Chapter 2: Structure, Properties, and Technical Challenges of Poly(lactic acid) (PLA)

Poly(lactic acid) (PLA) has established itself as one of the most promising biodegradable polymers.
from the market due to its excellent transparency, high modulus of elasticity,
biocompatibility and ease of processing by conventional transformation methods
of thermoplastics, such as injection molding, extrusion, and 3D printing by FDM. PLA
It is synthesized from the polymerization of lactic acid obtained by bacterial fermentation of plant sugars.1

Despite its ecological advantages, pure PLA has mechanical and thermal deficiencies.
which restrict its application to flexible packaging and durable commercial goods. The material
It has high rigidity and brittleness at room temperature, exhibiting deformation upon rupture.
typically less than 10%. This lack of ductility results in low impact resistance.
causing the polymer to fracture easily when subjected to mechanical stress.
traction or torsion.
The glass transition temperature *(Tg)* of pure PLA is in the range of 55 °C to 60 °C, which
Its use is limited in containers that come into contact with hot liquids or that remain hot.
exposed to high temperatures during transport. Furthermore, the crystallization rate of PLA is...
slow, requiring longer cycle times in industrial processing and resulting in a
Predominantly amorphous material with low thermal stability.
Another critical challenge for PLA concerns its biodegradability. Although the
If a polymer is categorized as biodegradable, its degradation through hydrolysis and subsequent...
Microbial assimilation occurs most efficiently primarily in industrial composting environments.2
, where temperatures maintained above 58°C and humidity controlled accelerate the
process. Under natural soil and freshwater conditions, the degradation of pure PLA is
extremely slow, and can take years to complete.
Therefore, overcoming the operational bottlenecks of the PLA requires modifying its structure.

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[1] Poly(lactic acid) (PLA) synthesis occurs primarily via ring *-opening polymerization* (ROP), a process that allows control of the polymeric stereostructure between L-lactide and D-lactide isomers, directly influencing the degree of crystallinity of the final thermoplastic.

[2] As specified by the international technical standards ISO 17088 and ASTM D6400, composting
The industrial processing of PLA requires controlled thermo-hygrometric conditions, maintaining thermophilic temperatures between 58 °C and 60 °C, relative humidity above 60%, and active microbiota to achieve 90% mineralization within 180 days.

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through the addition of or mixing with other compounds. The development of biocompounds that improve the flexibility of PLA and accelerate its natural biodegradability rate is the This is key to expanding the use of this biopolymer on a large scale in industry.

Chapter 3: Modification of Biopolymers with Plant-Based Plasticizers *(Ricinus) communis* L.)

The incorporation of low molecular weight plasticizers into the PLA matrix is the strategy. most efficient technique to increase the mobility of polymer chains and raise the Flexibility and ductility of the material. As Manrich (2006) teaches, plasticizers They act by positioning themselves between the macromolecular chains of the polymer, reducing the forces of intermolecular attractions and lowering the glass transition temperature *(Tg)* of the final compound. The use of castor oil *(Ricinus communis* L.) as a natural plasticizing additive. It offers a sustainable alternative to synthetic plasticizers derived from petroleum, such as phthalates.[3] , which exhibit high toxicity and a risk of leaching. Castor oil It has a unique chemical structure rich in ricinoleic acid, whose hydroxyl group confers partial polarity to the molecule, favoring its compatibility and interaction with the matrix of PLA ester.

The addition of controlled proportions of castor oil to PLA results in modifications. expressive changes in the mechanical and thermal properties of the compound. Tensile tests They demonstrate a significant increase in elongation at *break.* transforming the material's behavior from rigid and brittle to ductile and flexible. The effect The plasticizing effect also manifests itself in the reduction of *Tg,* allowing the compound to maintain its Flexibility at ambient temperatures and under refrigeration. Modifying the rheology and viscosity of the biocomposite melt facilitates its processing by extrusion and molding, reducing the pressure required in the die head. Machines and energy consumption during industrial transformation. The greater fluidity of Additive-enhanced material also optimizes the flow in slicing for additive manufacturing, allowing 3D printing of flexible parts with excellent layer-to-layer adhesion and a lower incidence of...

[3] Castor oil contains approximately 85% to 90% ricinoleic acid (12-hydroxy-octadec-9-enoic acid) in its triglyceride composition. The presence of the hydroxyl group (—OH) on the twelfth carbon of the fatty acid chain reduces the migration of the plasticizer and prevents exudation in polar polymeric matrices such as PLA.

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warping .

It is concluded that modifying PLA with *Ricinus communis* L. oil is a solution.

Innovative use of green chemistry applied to materials design. The use of an agricultural additive.

Renewable and non-food grade improves the mechanical performance of bioplastics, opening new possibilities.

Potential commercial applications in flexible packaging, protective films, and utilities.

commercial.

Chapter 4: Biodegradability Assessment in Soil and Industrial Applications of Packaging

Assessing the biodegradability rate of biopolymers under natural soil conditions is the

definitive parameter for proving the ecological efficiency of new materials intended for

Products with controlled shelf life. The environmental biodegradation process of additive-enhanced PLA.

It occurs in two consecutive stages: firstly, abiotic degradation by hydrolysis of

ester bonds in the polymer matrix are formed by the action of soil moisture, followed by degradation.

Biotic metabolism by microorganisms (bacteria and fungi) that consume the low molecular weight oligomers.

molecularly generated.

The incorporation of *Ricinus communis* L. vegetable oil significantly accelerates the process.

biodegradation of PLA in natural soil. The increase in hydrophilicity of the matrix and the creation

Larger free volume between macromolecular chains facilitates the diffusion of molecules.

Water enters the interior of the part, accelerating the hydrolytic breakdown of the polymer. The presence of oil

The plant also acts as a source of nutrients for the soil microbiota, stimulating the

Fungal colonization on the surface of the piece.

Mass loss tests by burial in soil demonstrate that PLA samples

Additives exhibit loss of structural integrity and disintegration in drastically shorter timeframes.

smaller when compared to pure PLA. Reduction in environmental decay time.

It ensures that, in case of improper disposal in the environment, the material will decompose.

naturally without generating long-lasting microplastics or accumulating in landfills.

restrooms.

The industrial applications of modified PLA biocompounds are concentrated in the sector of

Commercial packaging, single-use bags, agricultural films and product wrappers.

Fast-disposal consumption. The combination of adjustable mechanical flexibility,

Impermeability to oils and rapid assimilation by the soil makes these materials ideal for

Replacing non-recyclable plastics in fast-moving consumer goods supply chains

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(FMCG).4

In short, proof of the biodegradability of PLA with additives in natural soil validates the Material viability for the circular economy. Materials science applied to ecodesign. provides the industry with high-performance packaging solutions that are functionally sound and environmentally friendly. null and void after the end of its commercial life cycle.

Chapter 5: Hydrolytic Degradation Kinetics, Diffusion, and Lifetime Limitations of Biocompounds

Quantitative analysis of the durability of modified biopolymers requires modeling of kinetics of hydrolytic degradation and water absorption profile in the polymer matrix. From According to Crank (1975), the diffusion of solvents and water in amorphous polymeric matrices and Semicrystalline structures can be mathematically described by Fick's Second Law of Diffusion. one-dimensional:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

Where *C* represents the concentration of water inside the polymer at a position *x* and time t, and *D* is the diffusion coefficient of the material. The incorporation of castor oil alters the coefficient D, increasing the rate of moisture transport to the core of the matrix.

The acceleration of hydrolysis and the consequent reduction in product shelf life impose limitations. Techniques that should be considered in the industrial design of packaging. Degradation. premature deterioration of the material during the storage phase of long-shelf products . *life)* can compromise the barrier against gases and moisture, resulting in contamination or Deterioration of the packaged contents. The materials designer must balance the additive content. to ensure that the degradation rate remains low during commercial use and increases only after disposal on the ground.

Mechanical stability under conditions of high relative humidity represents another limitation. operational aspects of biopolymers with additives. Water absorption-induced plasticization can

[4] *Fast-Moving Consumer Goods* (FMCG) refers to the industrial class of consumer goods with high turnover and short lifecycles, a sector that accounts for the largest global demand for flexible films and disposable rigid packaging.

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cause progressive loss of structural rigidity in stacking packaging or boxes of
commercial transport. The use of thin biopolymer barrier *coatings*.
Slower degradation helps protect the packaging surface during logistics handling.
without compromising its overall biodegradability post-disposal.
In addition to shelf-life limitations, the industrial processing of modified PLA requires control.
Strict monitoring of the resin's moisture content before processing. The presence of residual water in
Polymer granules during extrusion or injection molding cause thermal cleavage.
and hydrolytic of the PLA chains in the plasticizing screw, reducing the molar mass of the polymer.
and generating parts with mechanical properties inferior to those designed.
It is concluded that understanding the kinetics of degradation and the limitations of use of
Biocomposites are essential for the safe application of renewable materials in industry.
Precise calibration of the additive rate ensures that the product rigorously fulfills its functions.
commercial protection during useful use, disintegrating quickly and safely at the end of
Your journey in the circular economy cycle.

Chapter 6: The Impact of Materials Science and Ecodesign on ESG Governance
Companies

The adoption of sustainable materials and investment in ecodesign research are no longer necessary.
Isolated R&D initiatives to become central pillars of the strategy.
Corporate governance and Environmental, Social and Governance (ESG). According to
McDonough and Braungart (2002) argue that true sustainable innovation requires companies to...
assume full responsibility for the fate of the materials they place on the market,
Eliminating toxic liabilities and reducing the consumption of finite fossil resources.
The *environmental* pillar of the ESG guidelines is directly strengthened by
Replacing synthetic resins with biodegradable biopolymers of renewable origin. A
Reducing the cumulative carbon footprint, from biomass cultivation to final degradation.
The product's impact on the ground is auditable and quantifiable through Cycle Lifecycle Analysis reports.
Life. Demonstrating real reductions in greenhouse gas emissions raises the...
company ranking in international sustainability indices.
The social and governance impact is reflected in the transparency of the value chain and in the added value.
from local agricultural raw materials. The use of vegetable oils from local crops (such as
The use of castor beans for the synthesis of ecological additives stimulates the development of agriculture.
Family-friendly and strengthens the regional bioeconomy. Transparent governance in the ecolabel of

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The products prevent the practice of false environmental claims *(greenwashing),* building a
A relationship of trust with consumers and investors.
The integration between product design and sustainable materials science gives...
Companies gain a sustainable competitive advantage. Anticipating increasingly stringent environmental
legislation that prohibits the use of single-use plastics of fossil origin.5 protects the
The company protects against regulatory fines and operational disruptions, ensuring business continuity and...
business expansion in the global market.
It is concluded that investment in research and application of modified biopolymers is a
The imperative of strategic vision and socio-environmental responsibility. The union between the science of
Materials, ecodesign, and ESG governance transform sustainability into the primary driver of
Innovation, efficiency, and the generation of lasting value for contemporary corporations.

Final Considerations

The research developed throughout this article shows that ecodesign and modification
The use of biopolymeric materials is essential for consolidating the circular economy in
Industrial manufacturing. Research shows that the incorporation of castor oil ...
communis L. to poly(lactic acid) (PLA) matrix successfully overcomes historical limitations.
It eliminates the fragility and rigidity of bioplastics, providing a flexible, processable, and durable material.
high commercial performance.
Proof of increased natural biodegradability rate in soil of the additive PLA
confirms the ecological viability of the solution for short-life products and packaging.
commercial. The acceleration of the hydrolysis and microbial assimilation process ensures that the
The material returns to nature as a biological nutrient, eliminating the generation of toxic waste.
and the accumulation of discarded plastics in the environment.
The physical characterization of water diffusion kinetics and hydrolytic degradation allows calibration
accurately determine the shelf life of biocomposites to meet shelf-life requirements.
from the packaging industry. The technical management of the additive rate harmonizes the requirements of
Logistical durability aligned with post-disposal environmental goals.

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5. Refers to international regulatory guidelines such as the European Union's Single-Use Plastics Directive.
European (EU Directive 2019/904) and US state regulations (such as California *Senate Bill 54* - SB 54) establish mandatory targets for reducing non-recyclable plastics and post-recycling accountability.
consumption.

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The study reinforces the role of Life Cycle Assessment (LCA) and the *Cradle to Cradle* model.
as guiding tools for the design of new products. The choice of plant-based additives
Renewable and non-toxic materials reduce the industry's carbon footprint and support the transition of systems.
productive for fully decarbonized models.
Furthermore, the application of these modified biocompounds in the packaging and product sector.
Utilities demonstrate the value of ecodesign in promoting ESG guidelines in the environment.
Corporate. Replacing fossil-based resins strengthens companies' reputations.
ensures compliance with stringent environmental laws and meets investor expectations.
and conscious consumers.

Furthermore, the continuation of research into the development of new biocompounds and the
Strengthening partnerships between universities and manufacturing industries is fundamental.
to scale up the production of these materials. The transfer of knowledge from the science of
Bringing polymers to the production market is the way to democratize access to packaging.
ecological and functional.
Given the climate emergency scenario and the urgent need to eliminate...
Plastic contamination, investment in biopolymer research and ecodesign leaves
to become a trend that will solidify itself as the backbone of the manufacturing of the future.
It is concluded that academic rigor and innovation in renewable materials are the forces capable
to transform the relationship between industry and nature. The union between intelligent design, the
Green chemistry and corporate responsibility establish the cornerstone for an industry.
truly sustainable, capable of generating high-quality products and promoting
Preserving the planet for the present and for future generations.

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