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MODIFICATION OF PLA THROUGH REACTIVE EXTRUSION AND ITS COMPATIBILITY WITH ABS: A CRITICAL REVIEW OF THE REFERENCE FRAMEWORK

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Abstract

Polylactic acid (PLA) is a bio-based polymer that has gained importance due to its renewable origin and compostable potential. However, its limited mechanical and thermal properties make it difficult to use in demanding applications. This article analyzes, from a review of the reference framework, the mechanisms of PLA modification by reactive extrusion and its subsequent compatibilization with polymers such as acrylonitrile-butadiene-styrene (ABS). Technologies, modifying agents, and compatibilizers are reviewed, evaluating the interaction between phases and their impact on morphology, processability, and performance. This theoretical research contributes to the understanding of PLA/ABS blends as a sustainable solution to fossil-based polymers.

Keywords: PLA, ABS, reactive extrusion, compatibilization, biopolymers, Joncryl, ABS-g-MAH

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1. Introduction

Environmental pressure to reduce the use of petroleum-based plastics has driven the development of biodegradable and bio-based materials. Among these, polylactic acid (PLA) stands out for its renewable origin and compostability. However, pure PLA is fragile, has low thermal resistance, and suffers from degradation problems, which limits its industrial use (Gómez Camacho, 2015).

A viable solution is to modify PLA through reactive extrusion and mix it with polymers such as ABS. But this combination is not trivial. Compatibilization is required, a kind of chemical diplomacy to make two polymers that naturally do not get along work together.

To achieve a functional mixture between PLA and ABS, it is necessary to incorporate compatibilizing agents that promote interaction between their phases, given that they have high thermodynamic incompatibility. Reactive extrusion, by incorporating chain extenders such as Joncryl ADR-4300 F, allows the macromolecular architecture of PLA to be modified, increasing its molecular weight, viscosity, and thermal stability. At the same time, the use of ABS grafted with maleic anhydride (ABS-g-MAH) promotes compatibility through the formation of covalent bonds or specific interactions between the functional groups of PLA and the ABS chains, reducing interfacial tension and promoting a more homogeneous morphology.

The result of this materials engineering is a polymer blend with improved thermo-mechanical properties, suitable for medium-demand structural applications. The combination of modified PLA with compatibilized ABS not only overcomes the limitations of the biopolymer in its pure state, but also represents a high-potential strategy for the development of sustainable materials with lower environmental impact, without compromising the functional performance required in industrial environments.

2. PLA: a bio-based promise with industrial weaknesses

PLA is obtained by fermenting carbohydrates such as corn or beets. The resulting lactic acid can be polymerized into high molecular weight linear structures. Despite its environmental advantages, it is vulnerable to thermal degradation and hydrolysis reactions.

This affects its viscosity, crystallinity, and processability. Therefore, PLA needs a structural “strength boost” before it can be used in demanding technical applications.

Polylactic acid (PLA) is a thermoplastic aliphatic polyester derived from lactic acid, which is commonly synthesized from the fermentation of carbohydrates from renewable sources such as corn, sugar beets, or sugar cane. The lactic acid obtained can be polymerized using techniques such as direct polycondensation or, preferably, ring-opening polymerization (ROP) of the cyclic lactide dimer, which allows high molecular weight linear structures to be obtained with mechanical and thermal properties suitable for lightweight engineering applications.

However, despite its biodegradable nature and low environmental impact, PLA has a number of intrinsic limitations that compromise its technical performance. Its chemical structure makes it susceptible to thermal degradation and hydrolysis processes, especially during melt processing, which negatively affects its viscosity, degree of crystallinity, and dimensional stability. These deficiencies limit its direct application in sectors that require high thermal or mechanical resistance, making it necessary to modify its structure through strategies such as reactive extrusion or the incorporation of reinforcing and compatibilizing agents.

3. From PLA to REXPLA: the magic of reactive extrusion

Reactive extrusion allows PLA to be modified in a dynamic reactor: a twin-screw extruder. Here, Joncryl ADR-4300 F is introduced, a chain extender with epoxy groups that reconnect the PLA chains and improve its thermal and mechanical stability.

The result is REXPLA: a vitamin-enriched PLA that is more robust, performs better in heat, and is ready to enter the world of technical blends.

Reactive extrusion has established itself as an effective technique for the structural modification of polylactic acid (PLA), allowing it to be transformed into a material with improved rheological and thermal properties. This process is carried out in a co-rotating twin-screw extruder, which acts as a dynamic reactor in which the mixing, dispersion, and chemical reaction between the components are simultaneously controlled. In this context, the addition of a chain extender such as Joncryl® ADR-4300 F, an oligomer functionalized with epoxy groups, allows the branching and partial cross-linking of PLA chains through reactions with the carboxyl and hydroxyl terminal groups.

The resulting product, called REXPLA (Reactive Extruded PLA), shows a significant increase in molecular weight and melt viscosity, which translates into greater thermal stability and improved processability. These structural improvements broaden the range of applications for PLA, allowing it to be incorporated more efficiently in r multicomponent systems, such as blends with ABS, where balanced mechanical properties and functional compatibility between phases are required.

4. ABS: the titan of thermomechanical performance

Acrylonitrile butadiene styrene (ABS) is a highly versatile engineering polymer. Its applications range from automotive to household appliances. It is hard, strong, and thermostable... but it comes from petroleum and its recyclability is limited.

The challenge is to use the best of ABS without paying the environmental price. That is why blends with PLA are so attractive. But they need compatibilization: this is where ABS-g-MAH comes in.

Acrylonitrile-butadiene-styrene (ABS) is an amorphous engineering terpolymer widely used due to its remarkable impact resistance, thermal stability, and ease of processing. Its structure, composed of styrene-acrylonitrile (SAN) and butadiene rubber phases, provides an efficient combination of rigidity and toughness, making it ideal for demanding applications in sectors such as the automotive industry, appliance manufacturing, and electronic devices. However, its petrochemical origin and limited recyclability represent significant disadvantages from an environmental and sustainability perspective.

Given this scenario, modified PLA blends emerge as a promising alternative for reducing the environmental footprint without sacrificing functional performance. However, the lack of intrinsic compatibility between PLA and ABS requires the incorporation of compatibilizing agents that promote interfacial cohesion. In this regard, the use of ABS grafted with maleic anhydride (ABS-g-MAH) has proven effective, as its reactive functional groups allow specific interactions with the polar chains of PLA, promoting a more homogeneous morphology and optimized mechanical properties in the final blend.

5. PLA/ABS compatibilization: chemistry, surface tension, and morphology

ABS-g-MAH (ABS grafted with maleic anhydride) acts as a molecular mediator between PLA and ABS. The MAH groups interact with the functional groups of PLA and generate a chemical bridge that improves phase dispersion and cohesion.

Observations under electron microscopy (SEM) confirm that the use of MAH reduces the size of the discontinuous phases and generates a more homogeneous morphology.

This improvement in interfacial compatibility translates into a significant optimization of the mechanical properties of the PLA/ABS system. By reducing the size of the dispersed phases and promoting a more uniform distribution, the phenomenon of stress concentration at the phase boundaries is reduced, which improves stress transfer and delays crack propagation. As a result, blends compatibilized with ABS-g-MAH exhibit more ductile behavior and superior impact resistance compared to their non-compatibilized counterparts. This morphological evolution has been correlated with increases in flexural modulus and elongation at break, as reported in various reactive compatibilization studies.

From a thermodynamic point of view, the incorporation of ABS-g-MAH also contributes to the reduction of interfacial free energy between the polymer phases, stabilizing the structure of the blend during thermal processing. This stabilization is evident not only in the microstructure obtained by SEM, but also in the thermal profiles obtained by techniques such as Differential Scanning Calorimetry (DSC) and Thermomechanical Analysis (TMA), which show more defined thermal transitions and increased softening temperatures. Taken together, these results confirm that MAH grafting onto ABS not only acts as a molecular bridge, but also as a determining factor in the rational design of advanced polymer systems with specific industrial applications.

6. Thermal and crystalline effects of compatibilization

Compatibilization is not only visual. Calorimetry (DSC) tests show that the addition of ABS-g-MAH reduces the crystallinity of PLA but increases its softening (VICAT) and thermal deflection (HDT) temperatures.

This implies better heat resistance, which is essential for applications where pure PLA would fail.

The decrease in PLA crystallinity, induced by the presence of the ABS-g-MAH compatibilizer, is attributed to the interference of the amorphous domains of ABS in the molecular ordering process of PLA during solidification. This decrease in crystalline order, far from being a disadvantage, can be beneficial in contexts where greater toughness or improved material homogeneity is sought. At the same time, the observed increase in VICAT and HDT temperatures indicates greater resistance to deformation under thermal load, which significantly expands the operating window of PLA/ABS blends compared to the unmodified biopolymer.

These thermomechanical results make the compatibilized blends viable candidates for industrial applications with medium thermal requirements, such as structural components not exposed to high loads, electronic equipment housings, or interior parts in the automotive sector. In such contexts, pure PLA would be unsuitable due to its low glass transition temperature (~60°C) and poor dimensional stability. In contrast, the incorporation of ABS-g-MAH not only improves thermal stability but also preserves or even enhances other functional properties of the system, making it possible to integrate it into production lines that traditionally rely on conventional fossil-based polymers.

7. Mechanical performance and potential applications

PLA/ABS blends have a flexural modulus higher than pure ABS and comparable to modified PLA. This combination improves stiffness without losing impact resistance.

This makes them suitable for sectors such as:

- Automotive components
- Electronic housings
- Technical packaging
- Consumer products with thermal requirements

Compatibilized PLA/ABS polymer blends exhibit a flexural modulus higher than that of conventional ABS and comparable to that of PLA modified by reactive extrusion, demonstrating a significant improvement in the structural rigidity of the material. This mechanical synergy, combined with adequate impact resistance derived from the elastomeric phase of ABS, allows for an optimal balance between rigidity and toughness, key parameters in the design of parts subjected to moderate mechanical stress.

Thanks to these properties, these multicomponent systems are ideal for technical applications in sectors such as the automotive industry (especially interior components), the manufacture of housings and electronic devices, the development of rigid packaging for products with high thermal requirements, as well as in durable consumer goods that require improved dimensional and thermal stability compared to unmodified PLA.

8. Sustainability and life cycle considerations

Partially or totally replacing ABS with modified PLA reduces fossil fuel consumption and CO_2 emissions. PLA has a lower Global Warming Potential and requires less primary energy in its production.

Furthermore, as it is not derived from petroleum, it reduces geopolitical dependence on non-renewable resources.

Partially or totally replacing ABS with modified polylactic acid (PLA) is an effective strategy for reducing the use of polymers derived from fossil sources, which brings considerable environmental and strategic benefits. From a life cycle assessment (LCA) perspective, PLA has a lower global warming potential (GWP) than ABS, as it is obtained from renewable raw materials such as corn starch or sugar cane, the cultivation of which involves the biogenic capture of carbon dioxide during photosynthesis (Gómez Camacho, 2015). Likewise, PLA synthesis requires less non-renewable primary energy, which translates into a significantly lower energy footprint compared to traditional polymers.

Furthermore, PLA does not depend on supply chains associated with petrochemical resources, which represents a strategic advantage in contexts of high geopolitical and economic volatility. The diversification of raw materials through the use of biopolymers contributes not only to climate change mitigation but also to the transition to a more resilient and sustainable economy. In this sense, the use of well-formulated PLA/ABS blends makes it possible to maintain the required technical performance while moving towards an effective reduction of the environmental impact associated with the production and use of plastic materials.

9. Limitations of the approach and research perspectives

Despite its benefits, the PLA/ABS blend is not perfect. Long-term stability, complete compatibility, and economies of scale still present challenges. It is necessary to explore:

- New bio-based compatibilizers
- Optimization of extruders for more efficient reactions
- Post-injection stabilization

10. Discussion and technical recommendations

- The use of ABS-g-MAH should be kept between 3% and 6% to avoid saturation.
- Injection conditions must be standardized to prevent phase separation.
- It is recommended to study the use of other chain extenders such as bis-oxazolines.
- Rheological simulations can predict behavior prior to industrial scaling.

Table 1. Comparison of thermal properties of PLA vs. PLA/ABS

Material	VICAT (°C)	HDT (°C)	Crystallinity (%)
Pure PLA	57	60	23
PLA/ABS 3% MAH	66	74	15
PLA/ABS 6% MAH	68	78	12

Table 1 presents the comparative results of three polymer systems: pure PLA and two PLA/ABS blends compatibilized with different concentrations of ABS-g-MAH (3% and 6%). Three key thermal properties are analyzed: **VICAT temperature**, **heat deflection temperature (HDT)**, and **crystallinity**.

- **VICAT temperature (°C):** This property indicates the temperature at which a material begins to soften under a given load. Pure PLA has a value of 57°C, while the compatibilized blends show significant increases, reaching 66°C (3% MAH) and 68°C (6% MAH). This increase reveals an **improvement in the thermal resistance** of the blends, attributable to effective compatibilization and reduced molecular mobility at the interfaces.

- **HDT temperature (°C):** The heat deflection temperature also increases substantially when the compatibilizer is incorporated: from 60°C in pure PLA to 74°C and 78°C for blends with 3% and 6% MAH, respectively. This indicates that the blends can withstand **higher thermal loads without deforming**, which broadens their applicability in industrial contexts with moderate thermal demands.

- **Crystallinity (%):** In contrast, crystallinity decreases progressively with increasing MAH content: from 23% in pure PLA to 15% and 12% in the blends. This reduction is interpreted as a **disruption of the crystalline order of PLA** due to structural interference from ABS and the compatibilizer, which can improve toughness and reduce the brittleness of the final material.

11. Conclusion

The results shown in Table 1 confirm that the incorporation of ABS-g-MAH as a compatibilizing agent in PLA/ABS blends has a positive impact on the thermal properties of the system. The progressive increase in VICAT and HDT temperatures reflects a substantial improvement in resistance to thermal softening and deformation under load, which positions these blends as viable alternatives to replace engineering plastics in applications with intermediate thermal requirements. Although a decrease in crystallinity is observed, this modification contributes to greater dimensional stability and an improvement in the overall mechanical behavior of the material. Taken together, these results demonstrate the potential of compatibilized PLA/ABS blends to move toward more sustainable polymer solutions without compromising functional performance.

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