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Programmed biodegradation capability of bio-based materials and products, validated in specific environments

MAGICBIOMAT

Manufacturing Guiding Tool for Circular and Programmed Biodegradable Materials Under Open Environment Conditions

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Authors

Author	Institution	Contact (e-mail, phone)
Alessandra Lorenzetti	**UNIPD**	**Alessandra.lorenzetti@unipd.it**
Lara Facchini	**UNIPD**	**Lara.facchini@phd.unipd.it**
Yuanyuan Chen	**TUS**	**Yuanyuan.chen@TUS.ie**
Ke Gong	**TUS**	**Ke.gong@TUS.ie**
Golnoosh Abdeali	**TUS**	**Golnoosh.Abdeali@TUS.ie**
Hilal Macit	**OK**	**H_gumusdere@organikkimya.com**

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Coordinator	**Yuanyuan Chen**	**27/01/2026**

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Point of Contact	Name: Yuanyuan Chen Partner: TUS (Coordinator) Address: Technological University of the Shannon, Athlone Campus, University Road Athlone, Co., Westmeath, N37HD68 Phone: +3530877663372 E-mail: yuanyuan.chen@tus.ie
Partners:	UNIPD, TUS, OK

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Acronyms

PBAT	Poly (butylene adipate-co-terephthalate)
PBS	Poly (butylene succinate)
PLA	Polylactic Acid
TPS	Thermoplastic Starch
WP	Work package

Executive Summary

This deliverable presents the initial outcomes of the MAGICBIOMAT project related to the development of bio-based and biodegradable polymer materials with tuneable properties and controlled degradation behaviour. Biodegradable materials are increasingly needed to reduce the environmental impact of plastic products; however, individual biodegradable polymers often exhibit limitations in terms of mechanical performance, durability, or degradation conditions. To address these challenges, this work explores polymer blending as a strategy to integrate the advantages of different biodegradable materials.

Several families of bio-based and biodegradable polymers, including polylactic acid (PLA), biodegradable polyesters, and thermoplastic starch (TPS), were investigated and combined using standard processing techniques. The resulting materials were evaluated to assess how different material formulations influence mechanical behaviour, processability, and expected biodegradation performance.

The results demonstrate that polymer blending is an effective approach to tailoring material properties and achieving a balanced compromise between mechanical performance and biodegradability. These findings provide a solid foundation for further material optimisation within the MAGICBIOMAT project and support the development of environmentally compatible materials suitable for applications with a controlled service lifetime, such as flexible packaging and agricultural films.

Intellectual property (IP) statement:

Certain technical details, including specific material grades, formulations, and commercial brand names, are not disclosed in this public version to ensure the protection of intellectual property (IP) and proprietary information. These details may be disclosed following the stabilization of intellectual property rights and appropriate confidentiality arrangements.

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1. Introduction

Plastics play an essential role in modern society, but their persistence in the environment has led to significant ecological challenges. In response, bio-based and biodegradable polymers have been developed as more sustainable alternatives. However, many biodegradable materials currently available on the market suffer from limitations, such as insufficient mechanical performance, restricted processing windows, or biodegradation that occurs only under specific industrial conditions.

The MAGICBIOMAT project addresses these challenges by developing materials whose biodegradation behaviour can be intentionally programmed and validated in real environments. A key strategy explored in the project is polymer blending, which enables the combination of different biodegradable materials in order to balance mechanical performance, processability, and environmental compatibility.

Within this context, the work presented in this public deliverable focuses on the development and preliminary evaluation of biodegradable polymer blends based on selected bio-based materials. By combining polymers with complementary properties, it is expected to overcome the limitations of individual materials and to design blends with tailored characteristics suitable for specific applications and environmental conditions.

This public deliverable provides an overview of the materials considered, the general experimental approach adopted, and the main trends observed in terms of material performance. The results function as a foundation for subsequent project activities aimed at further material optimization and validation of biodegradation behaviour.

2. Screening of starch and producing thermoplastic starch (TPS)

The objective of this part of the work is to evaluate the suitability of starch-based biodegradable polymer blends for applications that require limited-service life and controlled environmental degradation, such as packaging materials and agricultural mulching films. In particular, this study examines how the type and origin of starch influence the mechanical behaviour, thermal response, moisture sensitivity, processability, and recyclability of biodegradable polymer blends.

Starch was selected as a key component because it is abundant, renewable, biodegradable under natural conditions, and capable of significantly reducing the fossil-based content of polymer materials. However, starch properties vary widely depending on origin, which can strongly affect final material performance.

2.1. Raw Materials and blend compositions

The materials investigated in this study consist of commercially available biodegradable polymers, namely polylactic acid (PLA) and poly (butylene adipate-co-terephthalate) (PBAT), combined with starches derived from different natural sources, including wheat, potato, rice, tapioca, and corn. These materials were selected because they represent complementary biodegradable polymer systems commonly used in short-lifetime applications.

PLA is a bio-based polymer produced from renewable resources such as fermented plant sugars. It is widely used in packaging, disposable and agricultural products due to its relatively high stiffness, good transparency, and compatibility with conventional polymer processing techniques. However, PLA is inherently brittle and exhibits limited flexibility, which restricts its use in applications requiring high ductility. In addition, PLA typically biodegrades efficiently only under controlled industrial composting conditions, limiting its environmental performance in open environments. PBAT is a biodegradable polyester known for its high flexibility, toughness, and resistance to fracture. PBAT is capable of biodegrading under a broader range of environmental conditions, including soil, making it particularly suitable for applications such as flexible packaging films and agricultural mulching films. When used alone, however, PBAT generally exhibits lower stiffness and strength compared to PLA. Therefore, by combining PLA and PBAT, it is expected to balance stiffness and flexibility while improving overall mechanical performance and expanding the range of potential applications which makes PLA/PBAT systems particularly suitable for biodegradable film-based products.

Starches from different natural sources were also incorporated to further enhance biodegradability and reduce the fossil-based content of the materials. Starches differ significantly in molecular arrangement, particle size and morphology, and relative amylose and amylopectin content. These intrinsic differences strongly influence how starch interacts with polymer matrices during processing and how it affects the mechanical response of the final material. Depending on the starch source (Figure 1), the resulting blends may become stiffer and more rigid or, alternatively, more flexible but mechanically weaker. As a result, the choice of starch source plays a critical role in determining the balance between strength, flexibility, processability, and recyclability of biodegradable polymer blends intended for applications such as packaging and agricultural mulching films. To explore these effects, polymer blends containing different relative amounts of PLA, PBAT, and starch were prepared within a representative composition range (20-40wt.%). Specific material grades, suppliers, and detailed formulations are not disclosed in this public version.

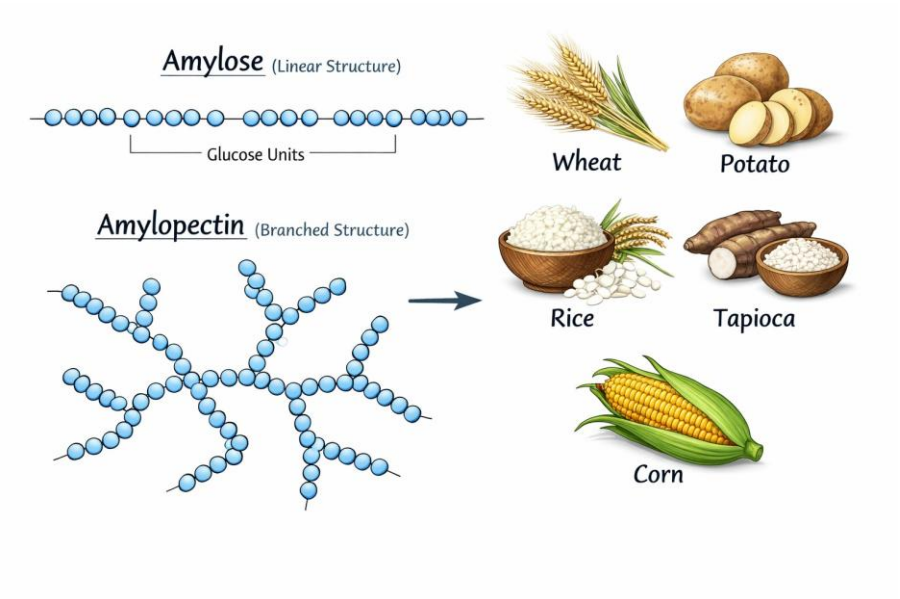


Figure 1. Schematic representation of starch structure with illustrative examples of sources of starch used in this project.

Table 1. Overview of biodegradable materials investigated in this study [1].

Material	Origin / Nature	Role in the Blend	Advantages	Limitations	Biodegradation Capability (Qualitative)	Typical Applications
PLA	Bio-based polymer from renewable plant resources	Provides stiffness and strength	Good mechanical strength, transparency, good processability	Brittle, limited flexibility	Primarily biodegrades under industrial composting conditions	Rigid packaging, disposable products
PBAT	Biodegradable synthetic polyester	Improves flexibility and toughness	High ductility, flexible	Lower stiffness compared to PLA	Biodegrades under soil and composting conditions	Flexible packaging, agricultural films
TPS	Natural polymer from agricultural starch	Enhances biodegradability, reduces fossil content	Renewable, rapid biodegradation	Moisture sensitive, low mechanical strength	Rapid biodegradation in natural environments	Short-lifetime products
PLA/PBAT blends	Blend of bio-based and biodegradable polyesters	Balances stiffness and flexibility	Improved toughness compared to PLA	Requires formulation optimisation	Biodegradability depends on blend composition	Flexible biodegradable films
PLA/PBAT/TPS blends	Polymer blend with natural starch	Enables controlled lifetime and biodegradability	Reduced fossil content, enhanced biodegradation	Reduced mechanical performance at high TPS content	Enhanced biodegradation compared to PLA-based systems	Agricultural mulching films

2.2. Methods

Polymer blends composed of PLA, PBAT, and starch were produced using melt-processing techniques representative of standard industrial practice. The materials were subsequently processed into films by compression moulding to enable evaluation under conditions relevant to real-world applications.

A series of established analytical methods was employed to assess key material properties, including mechanical behaviour, thermal response, and water vapour permeability. These properties are essential for determining the suitability of the materials for applications such as packaging films and agricultural products.

Processability was also evaluated to verify the feasibility of converting the materials from polymer pellets into final products using conventional manufacturing techniques. In addition, mechanical recyclability was assessed by subjecting selected blends to multiple reprocessing cycles (3 cycles). This step aimed to evaluate material stability upon reprocessing and to support circular economy strategies focused on reducing plastic waste and environmental impact in line with EU sustainability objectives.

2.3. Results and discussion

The investigated polymer blends exhibited clear qualitative differences in mechanical behaviour depending on both starch origin and starch content. In general, blends containing higher amounts of starch showed reduced mechanical performance, particularly in terms of flexibility, with increased stiffness and brittleness. This trend reflects the contrast between the high ductility of PBAT and the comparatively limited mechanical performance of thermoplastic starch (TPS).

Thermal behaviour was broadly comparable across all formulations, with only minor variations observed, indicating that the incorporation of starch from different natural sources does not introduce significant thermal stability concerns. Moisture response and water vapour permeability were also generally similar across formulations, ensuring comparable barrier performance for the intended applications (Table 2).

Several formulations demonstrated good stability after repeated reprocessing cycles, retaining acceptable overall performance with limited changes. This behaviour highlights the potential of these materials for use in circular material flows, where recycled content may partially substitute virgin material in packaging and agricultural applications.

Table 2. Qualitative overview of the influence of starch source on the mechanical behaviour, processability, and recyclability of biodegradable polymer blends, based on comparative screening results.

Starch source	Mechanical effect	Processability	Recyclability trend
Wheat	Moderate stiffness	Good	Moderate
Potato	Higher stiffness, lower ductility	Acceptable	Lower
Rice	Variable behaviour	Good	Moderate
Corn	Balanced strength–flexibility	Good	Above average (suitable)

2.4. Conclusions on starch screening

Task 1.1.1 successfully provided a comprehensive screening of starches derived from different natural sources for use in biodegradable polymer blends. The results demonstrate that starch origin significantly influences mechanical performance and recyclability, while thermal behaviour and moisture-related properties remain largely unaffected.

Based on the overall balance of mechanical performance and recyclability, **corn starch** source was identified as particularly suitable for the production of thermoplastic starch and subsequent polymer blends. This starch source was therefore selected as the reference material for further development in subsequent stages of the project, ensuring consistency and reliability in future material optimisation activities.

3. Development of compatibilizers

The development of compatibilizers is a key step in enabling the effective use of multi-component biodegradable polymer systems. While bio-based and biodegradable polymers such as PLA, poly (butylene succinate) (PBS), PBAT, and thermoplastic starch (TPS) exhibit complementary properties, they often show limited mutual compatibility due to differences in molecular structure, polarity, and chemical reactivity. Without compatibilization, these systems tend to exhibit phase separation, poor interfacial adhesion, and unstable mechanical performance, which limits their applicability in real-world products. Compatibilizers are therefore required to improve interfacial interactions between different polymer phases/blends (e.g. PLA/PBS, PLA/PBAT, PBAT/PBS, PLA/PBAT/TPS), ensuring a more homogeneous material structure and stable performance (Figure 2).

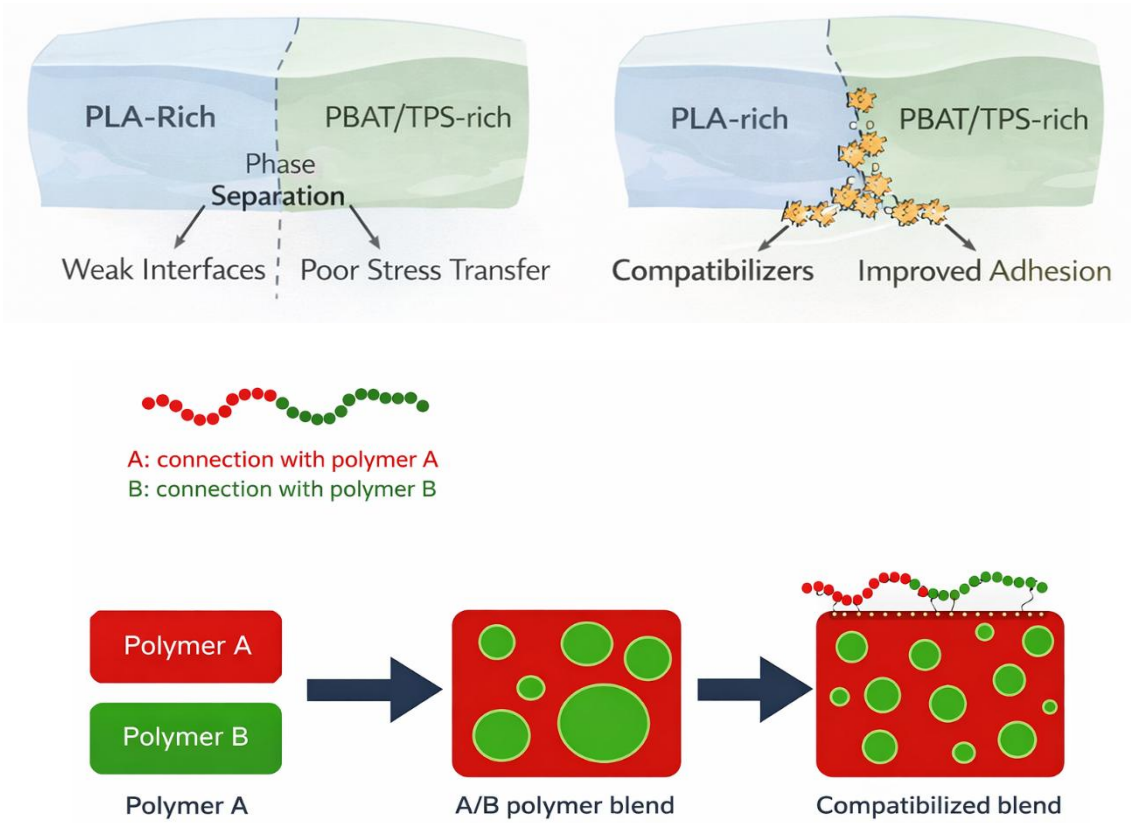


Figure 2. Conceptual illustration showing the role of compatibilizers in biodegradable polymer blends (PLA, PBAT, TPS). Without compatibilizers, different polymer components form separated phases with weak interfacial adhesion, leading to poor mechanical performance. With compatibilizers, interfacial interactions are improved, resulting in a more homogeneous structure, better stress transfer, and more reliable performance in flexible packaging and agricultural mulching films [2].

3.1. Raw Materials

The raw materials used for compatibilizer development were selected to enable the formation of multifunctional structures compatible with both biodegradable polyester-based and starch-based polymer systems. All reaction materials for compatibilizer development were commercially available and selected based on their relevance to bio-based polymer chemistry, industrial applicability, and ability to promote interfacial interactions. Bio-based building blocks representative of aliphatic polyester chemistry were included to ensure compatibility with polyester-rich phases such as PLA, PBAT, and PBS. Additional

components were selected to introduce functional groups capable of interacting with more polar phases, including TPS. This combination enables the design of compatibilizers that can effectively link chemically dissimilar polymer domains (Table 3).

Table 3. Overview of material classes used in compatibilizer development and their functional role in biodegradable polymer blends [3, 4].

Material class	General description	Functional role in compatibilizers	Relevance to target applications
Bio-based polyester building blocks	Renewable aliphatic polyester units	Ensure compatibility with polyester phases (PLA, PBAT, PBS)	Maintains mechanical stability in flexible films
Oligomeric polyester segments	Short polymer chains with tailored functionality	Act as interfacial linkers between different polymer phases	Improves homogeneity and mechanical consistency
Multifunctional components	Molecules with multiple reactive sites	Promote branching and network formation during processing	Enhances durability under mechanical stress
Polar functional components	Vinyl- or alcohol-based materials	Improve interaction with starch-containing phases	Supports compatibility in PLA/PBAT/TPS blends
Reactive initiators and modifiers	Components enabling controlled reactions	Enable in situ compatibilizer formation during blending	Industrially relevant reactive processing

3.2. Oligomer design and compatibilizer formation

Oligomer synthesis represents a critical step in compatibilizer development, as oligomer structure and functionality directly influence interfacial performance. In this work, oligomers were designed to exhibit selective affinity toward both polyester-rich phases and polar or starch-containing phases, allowing them to act as interfacial linkers within polymer blends. Reactive blending was selected as the compatibilizer production route due to its industrial relevance and scalability. Unlike simple physical mixing, reactive blending promotes in situ chemical interactions during processing, leading to the formation of compatibilizers with enhanced mechanical integrity and interfacial effectiveness (Figure 3).

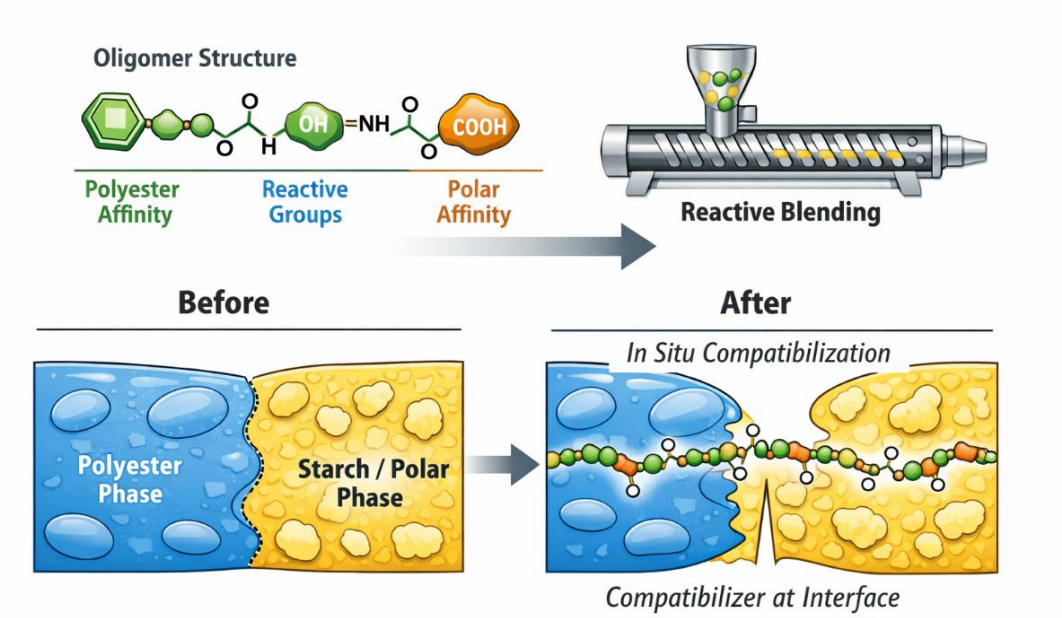


Figure 3. Schematic representation of oligomer-based compatibilizer formation via reactive blending, showing selective affinity toward polyester-rich and polar (starch-containing) phases and in situ interfacial linkage.

3.3. Conclusions on compatibilizers

The compatibilizer development method adopted in this work highlights the importance of rational material selection and functional design in multi-component biodegradable polymer systems. By qualitatively balancing performance, processability, and expected biodegradation behaviour, the developed approach supports the creation of stable and functional polymer blends. This strategy aligns with the objectives of programmed biodegradation and contributes to the development of sustainable materials suitable for flexible packaging and agricultural applications.

4. Developing biodegradable polymer blends with PLA, PBAT and TPS

Biodegradable polymers are commonly developed by blending different materials in order to achieve balanced performance for applications such as flexible packaging, bags, and agricultural mulching films. Individual biodegradable polymers often exhibit limitations when used alone; however, blending them allows their complementary properties to be exploited.

In this work, PLA, PBAT, and developed thermoplastic starch (TPS) from corn starch were blended to develop biodegradable polymer blends suitable for short-lifetime applications. PLA contributes stiffness and mechanical strength but is inherently brittle. PBAT provides flexibility and toughness, making the blends more resistant to fracture and better suited for film-based products. Thermoplastic starch (TPS) increases the renewable content of the material, can accelerate biodegradation, and helps reduce material cost, although it exhibits limited mechanical performance when used alone. By combining these three components, it is expected to improve processability, mechanical behaviour, and sustainability simultaneously. This approach enables the development of biodegradable materials that better meet both functional and economic requirements for flexible packaging films and agricultural mulching films (Figure 4).

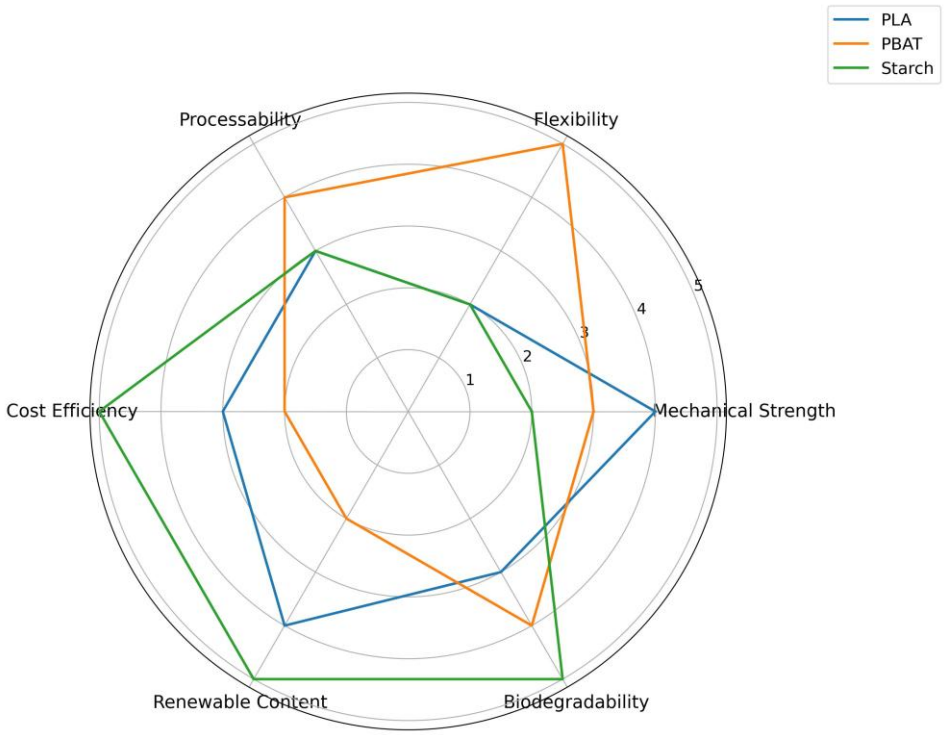


Figure 4. Radar chart comparing the main advantages and limitations of PLA, PBAT, and starch. The values are qualitative and intended to highlight the relative performance of each material.

4.1. Materials and Methods

A statistical optimisation approach, known as Design of Experiments (DoE), was used to vary blend compositions and evaluate their influence on material performance. The DoE approach enables the identification of key formulation parameters and their interactions while reducing the number of experimental trials required. This method supports efficient optimisation by minimising trial-and-error, saving materials, and accelerating development. Based on the outcomes of this optimisation process, additional blends were produced incorporating the compatibilizer developed on the previous section. The role of the compatibilizer is to improve interfacial interactions between the chemically different polymer components, which is expected to further enhance mechanical performance and material cohesion.

Two levels of thermoplastic starch (TPS) content were investigated to reflect different performance targets. Lower starch content is expected to favour mechanical strength and flexibility, while higher starch content is expected to enhance biodegradation behaviour at the expense of mechanical performance. This comparison supports the selection of formulations suitable for different application requirements.

Table 4. Overview of blend (PLA/PBAT/TPS) optimisation strategy and targeted performance objectives.

Parameter investigated	Variation approach	Purpose of variation	Expected impact on performance
PBAT / PLA ratio	Different qualitative levels using DoE	Balance stiffness and flexibility	Improved toughness while maintaining sufficient strength
Thermoplastic starch (TPS) content	Two representative levels (lower and higher)	Control biodegradation behaviour and renewable content	Higher TPS enhances biodegradability but may reduce mechanical performance

Parameter investigated	Variation approach	Purpose of variation	Expected impact on performance
Compatibilizer addition	Different qualitative levels	Improve interfacial adhesion between polymer phases	Enhanced material cohesion and mechanical stability
Overall blend composition	Optimised using statistical methods	Identify balanced formulations	Reduced trial-and-error and efficient material optimisation

4.2. Results and discussion

The comparative evaluation of the optimised PBAT/PLA/TPS formulations revealed clear and consistent trends in mechanical performance, processability, and expected biodegradation behaviour. Among the investigated compositions, two formulations were identified as offering the most balanced compromise between stiffness, flexibility, and material cohesion, while remaining suitable for processing into films starting from polymer pellets. These formulations demonstrated performance characteristics compatible with the requirements of flexible packaging films and agricultural mulching films.

Blends with lower thermoplastic starch (TPS) content exhibited improved mechanical strength and flexibility, reflecting the dominant contribution of the PBAT and PLA phases. In contrast, blends with higher TPS content showed reduced flexibility and increased stiffness and brittleness, consistent with the limited mechanical performance of thermoplastic starch. However, higher TPS levels are expected to favour faster biodegradation and increased renewable content, highlighting the trade-off between mechanical performance and environmental behaviour.

The introduction of a compatibilizer had a measurable impact on blend performance. At low compatibilizer levels, improved material cohesion and interfacial adhesion were observed, resulting in more stable mechanical behaviour without significant changes in flexibility or stiffness. At higher compatibilizer contents, an increase in stiffness accompanied by a reduction in flexibility was observed, indicating that excessive compatibilization can restrict polymer chain mobility and negatively affect deformability.

Thermal behaviour remained broadly comparable across all investigated formulations, both with and without compatibilizer addition. This indicates that neither variation in TPS content nor compatibilizer incorporation introduced thermal stability concerns within the processing and application-relevant temperature range. Similarly, rheological behaviour confirmed that the selected formulations remained processable using conventional film-processing techniques.

Based on this comparative evaluation, two PBAT/PLA/TPS compositions were selected as reference materials for further development in subsequent project phases. These formulations provide a reliable balance between mechanical performance, processability, and expected biodegradation behaviour, supporting their use as base materials for the incorporation of biodegradable additives and enzymatic systems in later stages of the project.

4.3. Conclusions on developing biodegradable polymer blends with PLA, PBAT and TPS

In conclusion, by a statistical method two blends with the most optimized properties have been identified. Based on these results, additional tests were performed using compatibilizer, to define its optimal content to further improve the properties of the blends.

The next steps will involve optimizing the processing conditions of the blend with the compatibilizer, focusing on temperature, mixing speed, and mixing time. Furthermore, compatibilizer will be further improved in terms of chemical composition to enhance compatibility with blends.

Table 5. Qualitative impact of formulation parameters on key performance characteristics of PBAT/PLA/TPS blends*.

Parameter / Formulation Change	Mechanical Strength	Flexibility / Ductility	Processability	Expected Biodegradability
Increased PLA content	++	–	++	–
Increased PBAT content	+	+++	++	+
Low TPS content (~20 wt.%)	++	++	++	+
High TPS content (~40 wt.%)	–	–	+	+++
Low compatibilizer content	++	+	++	+
High compatibilizer content	+	–	+	+
DoE-optimised blend	+++	++	+++	++

*: The symbols (+++, ++, +, –) indicate qualitative trends observed in this study, where "+++" represents a strongly positive effect, "++" a moderately positive effect, "+" a slightly positive effect, and "–" a negative effect relative to the other formulations investigated. These symbols do not represent measured values.

5. Development of PLA/PBAT, PLA/PBS, PBAT/PBS blends

5.1. Materials

Commercially available biodegradable polymers, including PLA, PBS, and PBAT, were investigated in this part of the work. These materials were selected because they represent commonly used biodegradable polymers with complementary properties but also inherent limitations when used individually. PLA offers relatively high stiffness and strength but is brittle and exhibits limited biodegradation under natural conditions. PBS and PBAT provide improved flexibility and ductility but generally show lower mechanical strength compared to PLA. To address these limitations, binary polymer blends (from 100:0 to 0:100 wt.%) were formulated to explore how blending these materials can improve overall performance and suitability for short-lifetime applications such as flexible packaging and agricultural films (Figure 5). Detailed information regarding material grades, suppliers, and blend compositions is not disclosed in this public version.

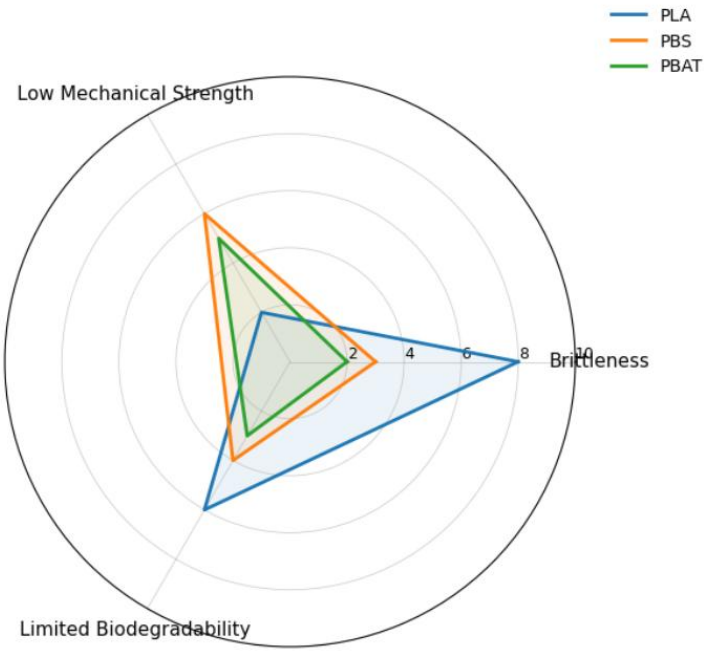


Figure 5. Radar chart illustrating individual drawbacks of PLA, PBS, and PBAT.

5.2. Processing routes: hot melt extrusion (HME), Injection Moulding (IM), compression moulding (CM)

Binary blends based on PLA/PBAT, PLA/PBS, and PBAT/PBS were produced using melt-processing techniques representative of standard industrial practice. The materials were subsequently processed using conventional moulding methods to generate specimens suitable for property evaluation (Figure 6). These processing routes reflect typical manufacturing pathways used for producing packaging components and film-based products.

A set of complementary analyses was performed to assess key material properties, including mechanical behaviour, thermal response, barrier performance, and material homogeneity. These evaluations support the identification of blends capable of meeting the performance requirements of practical applications.

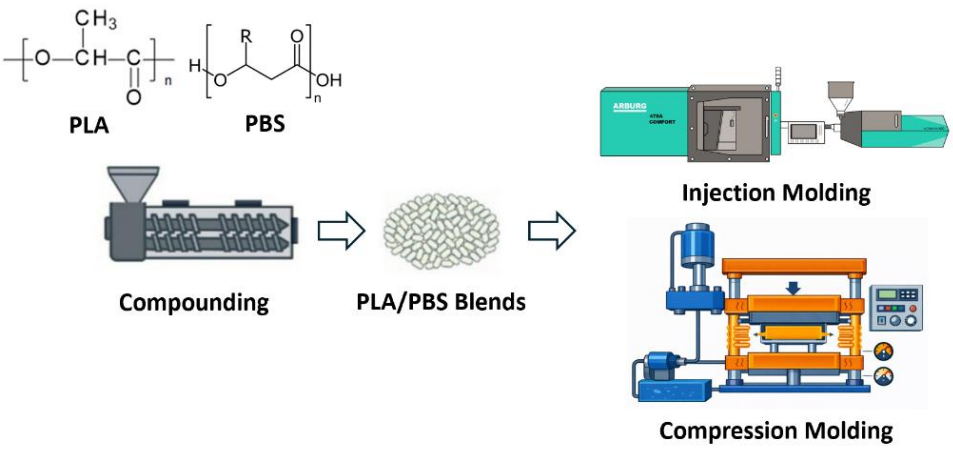


Figure 6. Sample manufacturing routes for PLA/PBS blends.

5.3. Results of selected blend loaded with the project-developed compatibilizer

Selection of reference binary blend

Based on the comparative evaluation of the binary blends, one formulation was identified as offering the most balanced combination of mechanical performance, thermal stability, and barrier behaviour. This blend demonstrated favourable overall performance compared to the other investigated systems and was therefore selected as a reference material for use in subsequent project work packages. To further improve interfacial interactions within the selected binary blends, the effect of compatibilizer addition was investigated. A compatibilizer developed within the project was compared with a commercially available reference compatibilizer (Joncryl® ADR 4468 Chain Extender from BASF Corporation, Germany) at equivalent loading levels.

The results demonstrated that the project-developed compatibilizer was more effective in improving mechanical performance, particularly in terms of strength and stiffness, compared to the commercial reference. This improvement indicates enhanced interfacial adhesion between polymer phases, leading to more stable mechanical behaviour.

5.4. Conclusions on the development of PLA/PBAT, PLA/PBS, PBAT/PBS blends

In summary, the evaluation of binary biodegradable polymer blends enabled the identification of a formulation with optimised overall performance. The incorporation of a project-developed compatibilizer further enhanced mechanical properties, demonstrating its potential for improving material cohesion in biodegradable polymer systems. The selected blend and compatibilization approach provide a robust basis for subsequent investigations, including biodegradability and ecotoxicity assessments in later phases of the project.

6. Conclusions

Task 1.1.1 enabled a comparative evaluation of starches derived from different natural sources, providing a clear overview of their influence on the overall behaviour of biodegradable polymer blends based on PLA, PBAT, and TPS. The activity highlighted qualitative differences in mechanical performance and mechanical recyclability depending on starch origin, while water vapour permeability and thermal stability were generally comparable across the investigated formulations. Based on these results, one starch source (corn) was identified as the most suitable option for the development of thermoplastic starch-based blends, due to its favourable balance between performance and recyclability. As a result, all ternary blends based on biodegradable polyesters and thermoplastic starch (TPS) developed in the subsequent stages of WP1 were formulated using thermoplastic starch (TPS) derived from this selected source.

Within Task 1.1.2, a range of compatibilizing systems was developed to improve interactions between the different components of the polymer blends. At a qualitative level, the introduction of these compatibilizers was shown to enhance blend homogeneity and overall mechanical balance, contributing to improved material cohesion without negatively affecting general performance. These findings confirm the relevance of compatibilization approaches for the further development of biodegradable polymer blends.

In Task 1.1.3, a preliminary comparative assessment of selected blend compositions was carried out to identify formulations offering an optimal balance between strength and toughness at different thermoplastic starch contents. This activity led to the identification of two reference blend compositions that demonstrated the most promising overall behaviour. Based on these findings, further evaluations were conducted by incorporating a selected compatibilizer, which proved particularly effective when used at low levels in blends with moderate thermoplastic starch content. Future activities will focus on the further optimisation of these compatibilized blends and their formulation to enhance overall material performance and compatibility, in line with the objectives of the project.

In addition, Task 1.1.3 addressed alternative biodegradable polymer blend systems based on different combinations of biopolyesters, including PLA, PBS, and PBAT. This work highlighted how the intrinsic characteristics of each polymer influence the overall performance of the resulting materials. Based on the observed qualitative behaviour, one blend formulation was selected as the most suitable candidate for subsequent biodegradability and environmental impact assessments in later project phases.

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