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Advances in the processability and heat sealing of recycled polyethylene and biobased polymers films for flexible packaging

Avances en la procesabilidad y termosellado de películas de polietileno reciclado y polímeros bio-basados para empaques flexibles.

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Resumen

La industria de empaques ha requerido de cambios drásticos en las materias primas tradicionales usadas para la fabricación de bolsas flexibles de un solo uso, con el fin de satisfacer los requerimientos actuales de sostenibilidad del mercado. Esta demanda creciente va encaminada cada vez más al uso de materiales reciclados, bio-basados, compostables o con propiedades de biodegradabilidad, por lo que es importante entender los efectos del uso de este tipo de materiales en el desempeño del empaque final. Una de las propiedades más críticas es la fuerza de sello, ya que garantiza la resistencia del empaque durante su uso y con ello la integridad de los productos que protege. Este artículo de revisión se centra en los avances recientes sobre las propiedades de termosellabilidad y en la fuerza de sello de películas flexibles compuestas por mezclas de polietileno de baja densidad reciclado (PEBD) y almidón termoplástico (TPS), dado que estas mezclas destacan por su relevancia frente a otras formulaciones gracias a su equilibrio entre sostenibilidad y funcionalidad. Así mismo, en la revisión se abordan algunos otros materiales biodegradables y compostables con el objetivo de analizar su estado actual en cuanto a las propiedades de termosellabilidad y fuerza de sello. Se analizan cuales son los beneficios de la incorporación de los materiales reciclados y biocompuestos, así como las limitaciones actuales relacionadas con el procesamiento, las propiedades mecánicas y la sostenibilidad. Un resultado importante de la revisión es que, en cuanto a las propiedades de termosellabilidad y fuerza de sello, los materiales biodegradables o biobasados aún no alcanzan valores requeridos para aplicaciones de empaque, mientras que el PE reciclado o mezclas de PE con TPS si logran cumplir con esta propiedad. Por otra parte, esta revisión resume los estudios recientes sobre las propiedades de termosellado de películas plásticas, las técnicas de procesamiento y el impacto ambiental que tienen estos materiales. Se concluye que el uso de películas PEBD/TPS representa una opción viable para empaques flexibles al combinar capacidad de termosellado con una mejora en la biodegradabilidad y reciclabilidad.

Palabras Clave: termosellado, PEBD reciclado, almidón termoplástico, biocompuestos plásticos, empaques flexibles.

Abstract

The packaging industry has required drastic changes in the traditional raw materials used for the manufacture of single-use flexible bags in order to meet the current sustainability requirements of the market. This growing demand is increasingly directed towards the use of recycled, bio-based, compostable or biodegradable materials, so it is important to understand the effects of the use of these materials on the performance of the final packaging. One of the most critical properties of flexible films is seal strength, as it ensures the strength of the packaging during use and thus the integrity of the products it protects. This review article focuses on recent advances on the heat sealability properties and seal strength of flexible films composed of blends of recycled low-density polyethylene (LDPE) and thermoplastic starch (TPS), since these blends stand out for their relevance compared to other formulations due to their balance between sustainability and functionality. Likewise, some other biodegradable and compostable materials are addressed in the review in order to analyze their current status in terms of thermosealability and

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seal strength properties. The benefits of incorporating recycled and biocompounds materials are discussed, as well as the current limitations related to processing, mechanical properties and sustainability. An important result of the review is that, in terms of heat sealability and seal strength properties, biodegradable or bio-based materials still do not reach the required values for packaging applications, while recycled PE or blends of PE with TPS can accomplish with this property. On the other hand, this review summarizes recent studies on the heat-sealing properties of plastic films, processing techniques and the environmental impact of these materials. It is concluded that the use of LDPE/TPS films represents a viable option for flexible packaging by combining heat sealability with improved biodegradability and recyclability.

Keywords: heat sealing, recycled LDPE, TPS, plastic bio-compounds, flexible packaging.

1. Introduction

In recent decades, we have been constantly concerned about the negative environmental effects of conventional plastics, which has driven the search for more sustainable alternatives in various industries, especially in the flexible packaging sector. Flexible packaging represents an important part of the global plastics market, as it provides solutions with excellent characteristics that make it very attractive, such as lightweight, durable and economical to protect a wide range of products. In addition, they should be useful for protecting electronic products or even keeping foodstuff for longer shelf life, or if the application are disposable bags they must be functional to clean pet feces on public parks. However, the predominant use of fossil fuel-derived polymers, such as polyethylene (PE), combined with poor disposal, has generated a significant accumulation of non-biodegradable plastic waste, intensifying our global environmental crisis (Tolinski, M., 2021).

2. Recycled materials and bio-compounds for flexible packaging

2.1. Emerging biopolymers as sustainable alternatives in flexible packaging

Currently, bio-based materials such as polylactic acid (PLA), polycaprolactone (PCL), and polybutylene succinate (PBS) are emerging as sustainable alternatives in the flexible packaging industry (Barmpaki et al., 2024; Coltelli et al., 2023; Govindan et al., 2023; İlaslan, 2024; Mazidi et al., 2024; Zhu et al., 2024). PLA, derived from renewable resources such as corn starch, has gained popularity due to its ability to biodegrade under industrial composting conditions, and is sought for use in packaging applications such as those used in food products. However, it has shortcomings in terms of thermal resistance, permeability and mechanical properties, which has force to develop research in order to improve: its performance through blends with other polymers, their flexibility by incorporating plasticizers or their strength through natural reinforcing fillers as nanocrystalline cellulose. (Jacob et al., 2024; Mazidi et al., 2024; Morris, 2022a; Palai et al., 2019).

PCL, on the other hand, stands out for its good flexibility and degradability in various environmental conditions. This material is known for its versatility in medical applications and in packaging where a high degree of flexibility is required (İlaslan, 2024). Despite these advantages, it is more expensive to produce than conventional polymers, which limits its mass use (Lim et al., 2020). In turn, PBS combines superior mechanical properties, excellent heat resistance, and also is a fully biodegradable material under different composting conditions, making it a promising option for the food and industrial product packaging industry. Unlike PLA, PBS has better compatibility with recycling and industrial processing processes, being a potential candidate for the replacement of petroleum-derived polymers (Ajji et al., 2023; Coltelli et al., 2023; George et al., 2023).

Cellulose, due to its abundance and low cost, has become a key foundation for developing flexible, biodegradable, and functional food packaging materials. In recent years, numerous studies have highlighted its ability to form films useful for food preservation. For instance, cellulose acetate-based films combined with polyethylene glycol and carbon nitride have been developed. These films are highly flexible, biodegradable, and exhibit antibacterial activity, successfully extending the shelf life of fruits such as strawberries (Zhang et al., 2024). Similarly, robust and eco-friendly biopolymer films based on gelatin and oxidized cellulose (derived from abundant biomass) have demonstrated safety, durability, and biodegradability, making them suitable for food packaging applications (Zhuang et al., 2017). Another promising approach involves regenerating cellulose from marine algae. Fully transparent and flexible films made from cellulose extracted from green algae have shown good mechanical strength and oxygen barrier properties, making them effective for packaging perishable foods (Saedi et al., 2023).

Additionally, researchers have explored cellulose films modified with antioxidants, nanoparticles, or natural extracts. These films can block UV radiation, inhibit bacterial growth, and help maintain food quality, while remaining biodegradable and environmentally sustainable. Their goal is to develop active, multifunctional packaging materials (Shen et al., 2023). Overall, these studies demonstrate that cellulose, due to its availability, affordability, and versatility, represents a highly promising alternative for the fabrication of flexible, biodegradable, and functional food packaging. Such innovations contribute to reducing reliance on conventional plastics while extending shelf life of food products.

Although these materials represent significant advances towards sustainable packaging solutions, they still face challenges related to their production cost and their integration into existing recycling chains. However, they remain an essential part of the transition towards greener packaging that is compatible with the goals of the 2030 Agenda (Vasilyev et al., 2022).

2.2. The role of recycled LDPE in flexible packaging

Low-density polyethylene (LDPE) is one of the most widely used polymers in the flexible packaging industry, due to its excellent properties such as mechanical strength and its relatively simple processing, as well as its low cost. However, the massive production of virgin LDPE from fossil sources has been raising concerns about its environmental impact and the long-term consequences it may cause. LDPE recycling has become a viable solution to reduce the volume of plastic waste produced every day, thus reducing the demand for virgin resources and minimizing carbon emissions (Morris, 2022a), but there are still some challenges to solve. The main concern is related to degradation of mechanical and thermal properties after being submitted to multiple processing cycles. As the material is recycled, the polymeric chains of LDPE tend to break down, resulting in lower tensile strength, lower elongation and reduced seal strength (Farley & Meka, 1994). However, it has been reported that, by adjusting processing parameters and adding stabilizers, it is possible to maintain adequate performance in recycled flexible films (Duigou et al., 2008). On the other hand, flexible packaging for food applications is becoming increasingly complex due to the incorporation of multiple layers of different materials to fulfill the requirements of the food industry. This could cause a recyclability problem of flexible films, consequently it becomes necessary to generate monolayer film technologies that are feasible to recycle. Such is the case of flexible PE films modified superficially with coatings that improve their barrier properties and hydrophobicity but maintain their recyclability as they are mono-material films (Carullo et al., 2023). The use of recycled LDPE in combination with biocompounds, such as TPS, offers an interesting alternative to overcome some of the limitations of recycling neat LDPE. This combination will not only improve the biodegradability of the final material, but will also fit the mechanical and sealing properties of modern flexible packaging to meet particular requirements (Vasilyev et al., 2022).

2.3. Thermoplastic starch (TPS) used in flexible packaging bio-compounds

Thermoplastic starch (TPS) has gained attention in recent years as a viable biopolymer for packaging applications due to its low cost, availability and biodegradability (Mohammadi Nafchi et al., 2013). Derived from renewable sources such as corn, potato or wheat, starch can be modified through plasticization processes to acquire thermoplastic properties, which makes it compatible with traditional processing methods such as extrusion, commonly used in synthetic polymers (Mtibe & John, 2023).

One of the main advantages of TPS is its ability to degrade in natural environments, which makes it an attractive option for short-life applications such as single-use packaging. However, the mechanical properties of TPS, such as tensile strength and elongation, are inferior to those of PE, limiting its direct application in flexible packaging (George et al., 2023). One route to increase the mechanical performance of TPS-based plastic materials is through making blends with other polymers, such as PLA (Li et al., 2011; Palai et al., 2019; Yoksan et al., 2021), polybutylene adipate-co-terephthalate (PBAT) (Garalde et al., 2019; Yoksan et al., 2021) and lignin (de S. M. de Freitas et al., 2021), which allows maintaining the biodegradable character of the composite. Nevertheless, the performance of these bio-compounds may still be insufficient for certain applications, so the use of blends with synthetic thermoplastics with higher strength, such as LDPE, could be a more feasible route. The main challenge in combining TPS with synthetic polymers is the immiscibility between the two phases, which can result in blends with heterogeneous microstructures and suboptimal properties (Parameswaranpillai, Jayakumar, Radhakrishnan, Siengchin, Radoor, Ramesh, et al., 2023). To deal with these challenges, research on some compatibilizers and plasticizers has shown promising results to improve the interaction between TPS and LDPE, leading to more homogeneous blends with better processing properties and performance in terms of seal and mechanical strength (Karim et al., 2021).

3. Heat-sealing properties of flexible films

3.1. Heat-sealing of biodegradable films

The heat-sealing process involves joining two plastic films through the controlled application of heat and pressure. Typically, this is achieved using a system composed of a Teflon-coated heating bar and an upper base equipped with a silicone block, as illustrated in Figure 1. The films are positioned between these two components, where heat partially melts their inner surfaces. When pressure is applied and the materials are allowed to cool, a strong and continuous seal is formed. This technique is essential for assessing the quality of materials intended for flexible packaging applications.

The study of the heat-sealing properties of biodegradable films has been reported in few research papers, since most research in this topic has focused on mechanical strength properties, biodegradability, barrier properties, thermal properties, and others (Barmpaki et al., 2024; Govindan et al., 2023). Among biodegradable plastics, PLA has shown the most commercial development for several applications. Studies have been conducted to determine the best heat-sealing conditions in films made with PLA, finding the optimum sealing temperature at 130 °C (Hashimoto et al., 2009). In some studies, the heat-sealing properties of PLA have been found similar to oriented polypropylene (Matthews et al., 2013). The use of PLA in flexible films for packaging applications has been limited by the stiffness of this material and poor moisture barrier properties (McCurdy et al., 2022). Because of this, blends of PLA with other biodegradable polymers, such as PCL, PBAT or starch, have been proposed. In general, by increasing the amount of these other degradable polymers the seal strength of PLA is reduced, so there are still challenges to overcome to achieve PLA-based flexible films with good heat-sealing properties (Bamps et al., 2022, 2023; Tabasi et al., 2015).

In a recent study of PLA/PBAT/PBS blends it was observed a direct correlation between seal strength and PBS content, and that this value also depends on the type of film manufacturing process (Chuakhao et al., 2024). Another research on seal strength (peel mode) for blends of PBS with polyesters obtained from microorganisms, (specifically PHBV), it was observed that this property decreases by increasing polyesters content. (Kamrit et al., 2022). Other research works have been focused on generating biobased films from soy proteins, obtaining good seal strength results (Lu et al., 2021; Ren et al., 2024); using acorn meal to produce fat packaging films with which acceptable seal strength for packaging application was also obtained (Chi et al., 2023) or by using gelatin to generate dry food packaging bags (Gamboni et al., 2023). Regarding the heat-sealing properties of TPS, the reported temperature range to obtain good seal behavior was set between 144 to 166 °C, although the seal strength values are very low compared to other materials as can be PLA or LDPE (Das & Chowdhury, 2016). On the other hand, the effect of moisture content on the heat-sealing properties of TPS from different botanical sources has been studied. It was found that higher moisture content favors the seal strength of films formed with this type of TPS (Suh et al., 2020).

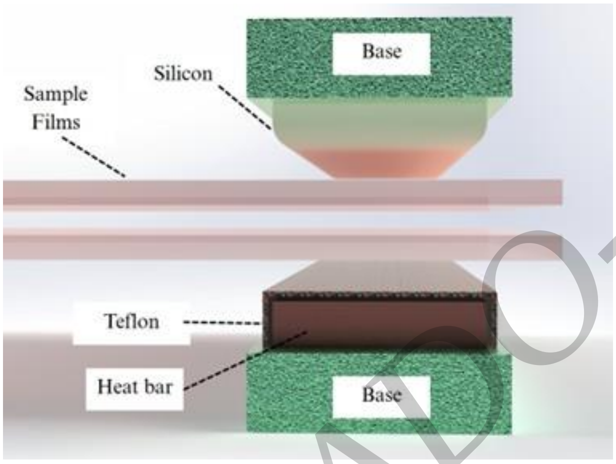

Figure 1. Heat-sealing process. (Prepared by the author)

3.2. Heat-sealing of recycled LDPE films

The heat sealability of recycled LDPE is a fundamental aspect in the packaging industry, as it ensures product integrity and protection against external factors. Recycled LDPE films with similar performance to virgin LDPE in terms of chemical resistance and flexibility, can experience degradation in their seal strength due to the reduction of crystallinity and polymer chain length during recycling processes (Farley & Meka, 1994). Studies have shown that the sealing properties of recycled LDPE films can be optimized by adjusting heat-sealing parameters such as temperature and pressure. Generally, it is recommended that recycled LDPE films be sealed at temperatures between 120°C and 130°C to obtain adequate performance (Hashimoto et al., 2012). In addition, the pressure applied during sealing should be sufficient to ensure full contact between the surfaces, hence improving seal diffusion. Despite these optimizations, results of some studies on seal behavior of recycled LDPE have evidenced that seal strength decreases slightly after recycling cycles compared to virgin LDPE, which could limit its use in applications where a high-performance protection is required (Ajji et al., 2023).

3.3. Heat-sealing of recycled LDPE/TPS films

Films composed of recycled LDPE and thermoplastic starch (TPS) represent a sustainable and functional alternative, especially in packaging applications that require biodegradability without compromising heat sealability. However, the integration of TPS into an LDPE matrix lead to challenges related to the immiscibility and dispersion of the polymer phases. These incompatibilities can generate weaknesses in the seal area, reducing seal strength (Parameswaranpillai, Jayakumar, Radhakrishnan, Siengchin, Radoor, & Giannakas, 2023). To improve the heat sealability of LDPE/TPS blends, studies have explored the use of compatibilizers, such as PE-grafted maleic anhydride (PE-g-MA), which promotes adhesion between the phases, resulting in improved compatibility and seal strength (Palai et al., 2019). On the other hand, it has also been shown that the use of plasticizers, such as glycerol or sorbitol, not only facilitates the processing of TPS, but also increases the flexibility and sealability of the films (Lim et al., 2020; Mtibe & John, 2023). In terms of sealing parameters, PE/TPS films show an optimal temperature range between 90°C and 100°C, with seal pressure around 0.2 MPa (George et al., 2023). Despite advances in control processing parameters, the seal strength of these LDPE/TPS films are still lower than neat-LDPE films, indicating that more research is needed to optimize their performance in packaging applications with high tear strength performance or prolonged exposure to mechanical stress.

3.4. Effect of additives and plasticizers on heat-sealing

Compounding extrusion is a technique used to blend polymers with functional additives, enhancing their final properties. In this process, base materials and additives—such as plasticizers, fillers, or compatibilizers—are fed into an extruder, where they are melted and mixed across specific zones: feeding, mixing, and pumping. The image illustrates how additives (in blue) are incorporated into the base polymer (in yellow), resulting in a homogeneous blend due to the mechanical action of the screws and the heat provided by the barrel (Figure 2). The final compound is obtained as it exits through the die, ready for further processing in applications such as blow molding or injection molding.

Additives and plasticizers play a crucial role in improving the processability and sealing properties of recycled LDPE and TPS composite flexible films. Glycerol is one of the most common plasticizers used due to its ability to reduce brittleness and improve processability on TPS blends by increasing the mobility of the starch polymeric chains, allowing layers to fuse more easily, hence improving heat-sealing (Gamboni et al., 2023). In addition to plasticizers, compatibilizers such as PE-g-MA have been shown to be effective in improving compatibility between the TPS and LDPE phases, allowing a more uniform distribution of the material during heat sealing. These additives not only increase seal strength, but also improve the thermal stability of the films under different conditions (Palai et al., 2019).

Table 1 shows seal strength values for several materials (commercial and research-developed) reported in the literature. These values were normalized to 15 mm wide samples to allow proper comparation. Typical seal strength values in a range from 0.5 to 10 N were observed. It is important to note that there is not much homogeneity between the thicknesses of the films evaluated in seal strength reported in the literature, so there may be differences related to this thickness difference, then it is not possible to analyze with the reported data. In terms of biodegradable thermoplastics, PLA has the highest seal strength values, but it must be considered that PLA is not a flexible material and requires blending with other materials. Regarding TPS, it has low seal strength values, so blends incorporating this type of biopolymer may have their heat-sealing strength properties affected. Another important issue is that the sealing temperatures used for the different materials vary significantly in a range from 85 °C to 170 °C. This is an important parameter because it means that the conditions of the sealing process must be adapted depending on the nature of the flexible film and as the recycling percentage or bio-based polymer amount increases. Besides, the use of recycled, bio-based or biodegradable compounds will affect the quality of the packaging products, then it is important to control seal quality through heat-sealing process parameters adjustment.

Figure 2 Blend compounding process. (Prepared by the author)

4. Processing methods for LDPE/TPS films

4.1. Blown film extrusion

Blown film extrusion is one of the most widely used techniques to produce flexible films in the packaging industry and has been adapted for processing recycled LDPE and TPS blends. In this process, molten polymer is extruded through a die, forming a tube that is inflated with air to create a bubble. This bubble cools and stabilizes as it is stretched, resulting in a continuous film of controlled thickness (Figure 3) (Tamber & Planeta, 2020).

Control of processing parameters, such as extrusion temperature, cooling rate, and drawing speed, is critical to ensure homogeneous phase distribution and avoid defects such as bubbles or inhomogeneity of the final film (Mtibe & John, 2023).

Research has shown that blown film extrusion of thermoplastic blends with TPS is more challenging than neat thermoplastic, such as PLA or LDPE, due to the higher viscosity of TPS and its tendency to absorb moisture, which can negatively affect the melt and stretch process (Ajji et al., 2023). One way to improve the processability of TPS is through the incorporation of high molecular weight plasticizers, such as xylitol or sorbitol (Dang & Yoksan, 2021).

Table 1: Heat-sealing characteristics of thermoplastic materials used in flexible packaging.

Material	Seal strength[a] [N]	Film thickness [µm]	Seal temperature [°C]	Reference
PLA	5 to 7	25	130 - 135	Hashimoto, Y. 2004
HDPE/LLDPE	3 to 6	50	123 - 125	Hashimoto, Y., 2012
Cellulose	0.60 to 2.01	38	130 - 150	
PLA	1.60 to 8.10	35	85 - 110	
OPP	1.60 to 10.85	20	115 - 145	Matthews J, 2013
OPP	1.8 to 10.50	35	115 - 145	
OPP	1.50 to 9.50	50	115 - 145	
PBS	0.6 to 9	800	95 - 120	Kamrit, P., 2022
PBS+PHBV	0.3 to 6	800	95 - 120	
Starch (AM)	0.149 to 0.396	65 - 105	85 - 166	
Starch (MC)	0.059 to 0.211	65 - 105	100 - 166	Das, M., 2016
Starch (HPMC)	0.217 to 0.385	65 - 105	85 - 166	
PLA/PBAT/PBS	8 to 16	30	N.D.	Chuakhao, S., 2024
Cassava starch	0.85 to 3.65	185 - 193	170	
Mungbean starch	1.65 to 4.05	185 - 193	170	Suh, J., 2020
Water chestnut starch	1.50 to 3.50	186 - 193	171	
Cassava starch	2.83 to 4.25	181 - 193	N.D.	Woo Su Lim, 2020
Soy protein	2.41	N.D.	139.5	Lu, J., 2021
PLA	14.37 to 22.62	55	130 - 160	McCurdy, C., 2022
LDPE	0.80 - 1.96	45	130 - 160	
Acorn seed meal/κ-Carrageenan	5.09	95	115	Chi, W., 2023
Gelatin	0.64	120	N.D.	Gamboni J. E., 2023
EVA	0.5 to 0.7	N.D.	60 - 119	Bamps, B., 2023
LDPE O2-coated	5 to 35	25 - 80	100 - 170	Carullo, D., 2023
Soybean protein pod extract	2.60 to 4.60	N.D.	110 - 130	Ren, Z., 2024

a Film sample wide of 15 mm; N.D. No reported data
* The acronyms are explained in Table A-1 as an appendix.

4.2. Flat extrusion and other processing methods

Another technique used in the manufacture of PE/TPS films is flat extrusion, in which the molten polymer is extruded through a flat die to form a thin film that is cooled on a roller (Figure 4). Although this method is efficient for producing films with uniform mechanical properties, it has some limitations when working with bio-compounds such as TPS, due to differences in the thermal properties of the blend components (Surendren et al., 2022).

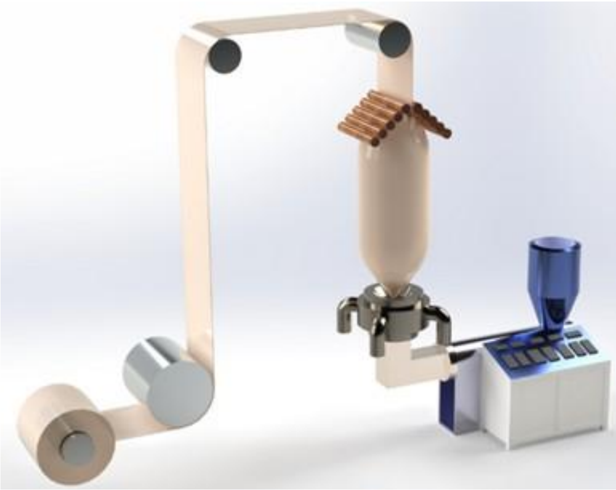

Figure 3. Blown film extrusion process. (Prepared by the author)

In addition to flat and blown extrusion, thermocompression has been explored as an alternative for PE/TPS film production on an experimental scale. This method involves compression of a PE and TPS blend at high pressure and temperature to form a thin film, although it is not as efficient as extrusion in terms of industrial scalability (Parameswaranpillai, Jayakumar, Radhakrishnan, Siengchin, Radoor, & Giannakas, 2023).

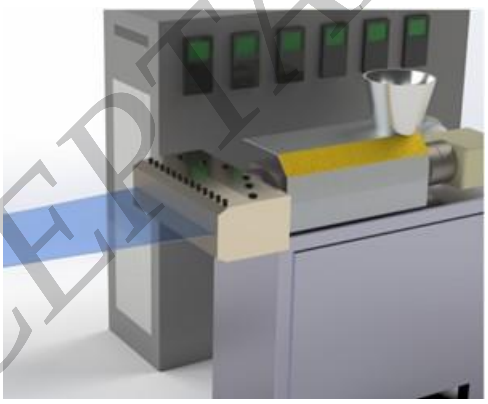

Figure 3. Flat film extrusion process. (Prepared by the author)

5. Environmental performance and sustainability of LDPE/TPS films

5.1. Biodegradability and recyclability

The sustainability of plastic materials has become a determining factor in the selection of polymers for packaging applications. The biodegradability of thermoplastic starch (TPS) is one of its main attractions, since this biopolymer can degrade under natural environmental conditions through the action of microorganisms, such as bacteria and fungi, accelerating its decomposition compared to conventional plastics (Bootklad & Kaewtatip, 2013).

Films composed of recycled PE and TPS present a duality of properties between the durability needed for flexible packaging and the ability to biodegrade. The presence of TPS in these films promotes the degradation process compared to neat PE, which contributes to the reduction of plastic waste in the long term. In addition, studies have shown that TPS not only improves the biodegradability of PE, but also acts as a promoter for the degradation of the biocomposite, especially when combined with natural additives that contribute to biodegradation (Oromiehie et al., 2013).

5.2. Environmental impact of production and the life cycle

The environmental impact associated with the production of flexible films from recycled materials and biocomposites has become a topic of great interest. As instance, PE/TPS films can have a significant positive impact compared to traditional alternatives based on virgin polymers, since it contributes to the reduction of the consumption of fossil resources and the amount of plastic waste generated (Tolinski, M., 2021).

Several life cycle analysis (LCA) studies have indicated that the use of biocomposites, based in biopolymers such as TPS, in flexible packaging could reduce greenhouse gas emissions and thus decrease the carbon footprint generated from this green packaging (Vasilyev et al., 2022). Furthermore, by recycling LDPE, the need to produce new LDPE from petroleum is reduced, resulting in a decrease in energy and resource consumption (Morris, 2022a).

However, TPS processing also requires optimization to reduce resource use, as some current production methods demand high energy and water consumption, especially during starch extrusion and plasticization (Mtibe & John, 2023). The implementation of more efficient technologies and the use of renewable energy can help improve the sustainability of these processes.

6. Importance of the transition to emerging materials and United Nations Sustainable Development Agenda

The adoption of emerging materials, such as flexible films composed of recycled LDPE and TPS is aligned with the sustainable development goals (SDGs) of the United Nations's 2030 Agenda, specifically those related to responsible production and consumption (SDG 12) and climate action (SDG 13). The 2030 Agenda promotes the reduction of the environmental footprint of industrial processes and encourages the transition to a circular economy, in which recycled materials and bio-compounds play a key role in decreasing dependence on fossil resources and reducing plastic waste.

The use of biocomposites such as TPS, alongside recycled polymers, offers a viable solution to achieve the goals set out in the United Nation's 2030 Agenda, which stipulates that, by 2030, at least 30% of plastic products should contain recycled material (United Nations, 2018). These kinds of initiatives help to reduce both plastic waste and carbon emissions during the production of virgin polymers and at the same time promote innovation in more sustainable packaging.

The incorporation of these emerging materials into the flexible packaging industry also contributes to closing the plastic product cycle by facilitating both recyclability and biodegradability. This transition to eco-friendly materials is fundamental for achieving more sustainable production and minimizing environmental impact, aligning with global efforts to mitigate the effects of climate change and preserve natural resources for future generations.

7. Challenges and perspectives

7.1. Immiscibility and mechanical properties

One of the main challenges in the development of PE/TPS films is the immiscibility between TPS and PE. This lack of compatibility between the components can lead to blends with heterogeneous microstructures, which affects negatively both the mechanical properties and heat-sealing of the material (Palai et al., 2019).

Recent studies have shown that the incorporation of compatibilizers, such as PE-grafted maleic anhydride (PE-g-MA), can significantly improve the interaction between both PE and TPS materials, resulting in enhanced sealing properties and mechanical strength (Jasso-Gastinel et al., 2017). Still, optimization of the formulation of these blends remains a critical area of research, as small variations in composition or processing methods can drastically alter the performance of the material.

On the other hand, the addition of other biodegradable polymers, such as PLA or PBAT, has also shown promising results in improving the properties of PE/TPS films. These combinations not only improve the biodegradability of the final product, but also provide higher flexibility and tensile strength (Dang & Yoksan, 2021).

7.2. Industrial Scalability and Cost

The economic viability of large-scale PE/TPS films presents another major challenge. Although the use of TPS reduces costs compared to virgin polymers, its production and processing still require improvements to compete with conventional plastic materials (Morris, 2022b). Current blown extrusion technologies face difficulties handling the high viscosity of TPS and its tendency to absorb moisture, which complicates control of the process and increases operational costs (Surendren et al., 2022).

To overcome these processing challenges, extensive research on processing technologies is needed to enable efficient and cost-effective large-scale production of PE/TPS films. Furthermore, investment in research and development of new materials, such as additives or plasticizers, could further reduce production costs and enhance the quality of the final product.

8. Conclusion

The transition to products based on emerging materials, such as flexible films composed of recycled LDPE and TPS, represents a significant step in the pursuit of sustainable solutions for the packaging industry. These materials not only provide an effective response to the plastic waste issue but also are aligned with the objectives of the United Nation's 2030 Agenda, particularly regarding responsible production and consumption and climate action.

Despite technical challenges, such as the immiscibility of PE and TPS phases and the optimization of their mechanical and heat-sealing properties, recent advances in the use of compatibilizers and plasticizers have shown that the performance of these bio-compounds can be significantly enhanced. Integrating these materials into industrial processes also contributes to reducing the environmental footprint and promoting the circular economy, where recycling and biodegradation are fundamental.

The implementation of PE/TPS films in the global market not only helps meet the sustainability requirements mandated by the 2030 Agenda but also positions the packaging industry as a key player in combating climate change and reducing plastic waste. However, for this transition to be fully successful, further research and development of new technologies are needed to enable the efficient and economically viable large-scale production of these materials.

The future of flexible packaging is expected to be directed towards the use of bio-compounds and recycled materials that ensure both functionality and environmental sustainability, with PE/TPS films serving as a clear example of the advances already being achieved in this field.

The selection of the PE/TPS blend is justified by its potential to balance mechanical properties and heat sealability, its relevance to the inevitable blending of these materials in recycled products, and its contribution to improving the environmental profile of the resulting material. Altogether, these attributes make the blend suitable for packaging applications. The findings highlight the positive impact of TPS in the formulations without significantly compromising the overall functionality of the packaging.

9. Appendix

Table A-1: Acronyms of the materials mentioned in the text

Material acronym	Description
PLA	Polylactic acid
HDPE/LLDPE	High-density polyethylene / Linear Low-density polyethylene
OPP	Oriented polypropylene
PBS	Polybutylene succinate
PBS+PHBV	Polybutylene succinate + Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

Starch (AM)	Starch with Amylose Matrix
Starch (MC)	Starch with Methylcellulose
Starch (HPMC)	Starch with Hydroxypropyl methylcellulose
PLA/PBAT/PBS	Polylactic acid / Polybutylene adipate terephthalate / Polybutylene succinate
LDPE	Low-density polyethylene
EVA	Ethylene vinyl acetate

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