

SUSTAINABLE FOOD PACKAGING

BASED ON

POLYHYDROXYALKANOATE

MSc in Resource Recovery
Polymer materials for circular economy

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Abstract

The Norwegian Food Research Institute (Nofima) and the University of Borås worked together to develop this project. The commonly used packaging materials pose a serious threat to the environment, as they are produced from nonrenewable crude oil and cannot decompose naturally. Despite some manufacturers' claims of their products being eco-friendly or sustainable, they are not entirely made from renewable resources and are not biodegradable. Nevertheless, some bio-based materials have emerged as a viable alternative that can naturally break down and safely decompose in the environment. Despite many studies, biopolymers possess limited mechanical and barrier properties, which restricts their potential for use in products. To overcome this limitation, polymer blending can be employed to enhance their final properties and make them more suitable for various applications.

The objective of this project was to design sustainable food packaging using biopolymers. PHBV, one of the PHA's bio-based polymers, was blended with other polymers to enhance its properties as a sustainable food packaging material. Through blending, PHAs' physical, chemical, and thermal properties can be enhanced to obtain exceptional films for food packaging purposes.

Finally, in this work, a bio-based polymer, polyhydroxyalkanoate, was used to produce a biodegradable packaging system for potential food packaging applications. The effect of the physical modification of PHBV on mechanical and barrier properties was studied by blending it with biodegradable polymers such as PLA and PBAT. Thermal properties were analyzed using differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and Fourier-

transform infrared spectroscopy (FTIR) while the mechanical properties were evaluated by tensile test. Barrier properties were characterized using water vapor transmission rate (WVTR).

The mechanical performance of PHBV 50%: PBAT 50% blend has been significantly improved, leading to better tensile properties. The high crystallinity of the PHBV 50%: PBAT 50% blend than other blends have been found to enhance the barrier properties of the polymer film, according to DSC analysis. FTIR investigations have suggested no difference in absorption peaks between the blends and the neat material. Furthermore, WVTR investigations have shown that PHBV50%: PBAT50% exhibits excellent barrier properties against water vapor, making it a highly promising material.

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TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. BACKGROUND AND PROBLEM DESCRIPTION.....	3
3. RESEARCH QUESTION	4
4. PURPOSE AND LIMITATIONS OF THE WORK.....	4
4.1 Purpose.....	4
4.2 The limitations of packaging systems	5
5.LITERATURE REVIEW.....	6
5.1 Circular economy and packaging	6
5.2 Eco-Friendly food packaging	7
5.3 Materials requirement	8
5.4 PHAs.....	9
5.5 PHBV	13
5.6 PLA	15
5.7 PBAT	18
5.8 Polymer blends.....	20
5.9 PHBV, PLA, PBAT blends.....	21
6. DESCRIPTION OF METHODS.....	23
6.1 Modification of PHAs.....	23
6.2 Physical Modification of PHAs	23
6.3 Blending	24
6.3.1 Twin-screw extruder.....	24
6.3.2 Injection molding	25
6.3.3 Film extrusion	26
7. CHARACTERIZATION.....	27
7.1 Tensile test.....	27
7.2 Differential Scanning Calorimeter (DSC).....	27
7.3 Fourier Transform Infrared Spectroscopy (FT-IR)	28

7.4 Thermal gravimetric analysis (TGA).....	29
7.5 Oxygen and water vapor barrier (WVTR)	29
8. RESULTS AND DISCUSSION.....	30
8.1 Tensile test.....	30
8.2 DSC	32
8.3 FTIR	37
8.4 TGA	40
8.5 Oxygen and water vapor barrier (WVTR)	43
9. CONCLUSION	44
10. PERSPECTIVE FOR THE FUTURE	45

List of Figures

Figure 1:Packaging materials requirements.	9
Figure 2: PHAs Structure (Gomes Gradíssimo et al., 2020)	12
Figure 3: PHBV structure (Boufarguine et al., 2013)	14
Figure 4:PLA structure (Boufarguine et al., 2013)	15
Figure 5:PBAT structure (Nobrega et al., 2012)	19
Figure 6:Physical modification through blending will be used in our current project.....	23
Figure 7:Polymer blending	24
Figure 8:Thermo Fisher Process 11 Extruder.....	25
Figure 9:Injection moulding	25
Figure 10:conveyor belt section.	26
Figure 11:Compression moulding	27
Figure 12:Elongation at break	32
Figure 13: Crystallinity of neat materials.....	33
Figure 14: Crystallinity of 75% :25% blends.....	33
Figure 15 Crystallinity of 50%:50% blends	33
Figure 16: Neat materials enthalpy curves	34
Figure 17: Enthalpy cure for 75%:25% blends	34
Figure 18: Enthalpy curve for 50%:50% blends	34
Figure 19:FTIR neat materials	37
Figure 20:FTIR results, PHBV & PLA blends	37
Figure 21:FTIR results, PHBV & PBAT blends.....	38
Figure 22:TGA weight results, neat materials	41
Figure 23: TGA weight results 75%:25% blends.....	41
Figure 24:TGA weight results 50%:50% blends.....	41
Figure 25:TGA Derive weight, neat materials.	42
Figure 26:TGA Derive weight 75%:25% blends.	42

Figure 27:TGA Derive weight 50%:50% blends.	43
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List of tables

Table 1:Tensile properties	30
Table 2:Summary of Modulus properties.....	31
Table 3:DSC results of PHBV, PLA, PBAT and their blends	35
Table 4:WVTR results of PHBV, PLA, PBAT and their blends.	44

Abbreviation

PHAs Polyhydroxyalkanoate

PHBV Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

PLA Polylactic Acid

PBAT Polybutylene adipate terephthalate

DSC Differential scanning calorimetry

TGA Thermogravimetric analysis

FTIR Fourier-transform infrared spectroscopy

T_g glass transition temperature

1. INTRODUCTION

Food packaging is a crucial aspect part of the food industry, and it has rapidly developed in recent decades. This is due to the food industry's response to social and economic changes. There are various types of packaging used for food, such as trays, bags, cans, films, coated paper cans, and plastic wrap. The design of food packaging is an effective way to protect and extend the shelf life of food products (Risch, 2009).

The role of packaging in ensuring the quality of food products cannot be overstated. It provides protection against various environmental, chemical, and physical challenges (Grönman et al., 2013). The protection can range from creating barriers against moisture, oxygen, carbon dioxide, flavors, and aromas. Packaging can also block light to ensure that nutrients and colors do not deteriorate. Besides passive protection, many packages today are active in maintaining the desired atmosphere around the product (Risch, 2009).

For the last many years plastics have been broadly used for manufacturing packaging materials because of their performance. With the arrival of food processing industries there is a significant demand for packaging materials for food applications. However, increased use of plastics has created serious ecological problems because of their resistance to biodegradation (Mangaraj et al., 2019).

A considerable development in the EU's action plan was realized in 2018 when the European Commission adopted their plastics strategy "A European Strategy for Plastics in a Circular Economy. The strategy includes proposals to modernize EU waste legislation (Matthews et al., 2021). One of the goals of the strategy is to make all plastic packaging placed on the EU market either reusable or recyclable by 2030. The Commission has also launched the Circular Plastics Alliance (CPA) to mobilize action from all players in the plastic value chain, from plastic producers and designers, through brands and retailers, to recyclers (COMMISSION, Brussels, 16.1.2018).

The global waste crisis is greatly affected by the issue of packaging waste, accounting for half of all waste produced around the world. Unnecessary and excessive packaging practices can contribute to various forms of pollution and generate more waste. It is unfortunate that most packaging is designed for single use, is not recyclable, not biodegradable, and is often disposed of instead of being reused, leading to pollution in our air, water, and land (Ferrão et al., 2014). However, food packaging has become more functional as it plays a vital role in drastically reducing food waste and protecting food throughout the supply chain. Various types of packaging help many food products stay fresh for longer and protect the product during

distribution. Undoubtedly when packaging is improved and increased to reduce food waste, the amount of packaging waste increases. It should be noted that the compostable and biodegradable packaging options help mitigate the environmental impact of packaging waste. Additionally, packaging that is designed for easy recycling or compostable can contribute to a more sustainable and circular economy (Grönman et al., 2013).

Since the demand for bio-based packaging solutions is growing worldwide; it is well known that biodegradable polymers have emerged as a promising alternative to common synthetic polymers to address environmental issues in recent years (Nilsen-Nygaard et al., 2021). The European Union has been investing heavily in researching new developments in packaging materials to address environmental concerns in the packaging industry. Companies and stakeholders consider adopting eco-innovative packaging solutions. The next generation of food packaging should significantly reduce waste in both food and packaging materials, and minimize negative impacts on the environment in alignment with circular economy principles (Altalhi, 2022). The next generation of the packaging materials solutions should help contribute to the overall decrease of food waste and deter plastic accumulation (Keränen et al., 2021). Regardless of having number of benefits over synthetic polymer, their uses have been restricted by the poor physical and mechanical properties, low compatibility with standard thermal processing techniques, susceptible to thermal degradation, and high production costs.(Berthet et al., 2015)

Using bio-based plastics instead of traditional plastics is a promising way to reduce the environmental impact of plastic production and disposal. These plastics are made from renewable resources, like plant-based materials, and can have a lower carbon footprint than fossil-based plastics (Song et al., 2009). The mechanical properties of bio-based plastics depend on the material and its intended use. Studies indicate that bio-based plastics typically have weaker mechanical strength than traditional plastics. Nevertheless, recent advancements in bioplastic production have resulted in the creation of materials with mechanical properties comparable to those of traditional plastics (Song et al., 2009).

As a result, replacing conventional plastics with PHAs remains a significant obstacle. Consequently, PHAs could be altered through blending with other polymers to achieve specific properties, for example, feasible degradation rates, flexible mechanical properties, surface elements and crystallinity (Risch, 2009). This thesis provides insight into the process of physical modification as well as a variety of perspectives on blending, including the kinds of blends that have already been shown to be practical (Berthet et al., 2015). PHAs' physical, chemical and barrier properties can be enhanced through blending, which can also lower

production costs. Currently, research is being conducted to encourage the use of PHAs blends in everyday activities. In the future, it is likely that PHAs and their blends will replace conventional plastics in applications, reducing plastic waste for the benefit of the environment (Kumar et al., 2021).

2. Background and problem description

Although PHAs have potential as biomaterials and as a competitor to traditional synthetic plastics, there are some drawbacks that limit their use. These include poor mechanical properties, limited functionalities, incompatibility with conventional thermal processing techniques, and susceptibility to thermal degradation (Masood, 2017). To address these issues, PHAs can be modified by blending with natural materials or other biodegradable polymers, chemical functionalization, and further research to improve brittleness and biodegradation control. Overall, improvements in PHAs can expand their uses in specific applications (Masood, 2017, Koller, 2014).

PHAs have the potential to offer more sustainable and environmentally friendly packaging options, particularly for food packaging. When considering the utilization of PHAs in film packaging, there are certain challenges and limitations that must be considered. One such challenge is the potentially high production costs associated with PHAs. Additionally, PHA-blended films, which are often made with cellulose, can be brittle and possess weak mechanical properties (Tan et al., 2014). It is crucial to address these challenges to guarantee that PHA-based films can be extensively adopted for packaging applications. Ongoing research and development work are aimed at enhancing the mechanical properties and cost-effectiveness of PHA-based films for packaging (Requena et al., 2016).

Polyhydroxyalkanoates (PHAs) are bio-based biodegradable linear thermoplastic polymers that can be produced by many microorganisms as intracellular carbon and energy stocks (Kennouche et al., 2016). Due to the hydrophobicity of these water-insoluble polyesters, PHA films display a very high-water vapor barrier property. In addition, PHAs show high barrier properties for oxygen, water, and CO₂. Nevertheless, the usage of as-is PHAs, that is, without blending with other polymers, is refrained by the narrow process window, high crystallinity and brittleness which makes the extrusion and other polymer processing difficult (Kumar et al., 2021). A possible solution to this problem could be blending PHAs with other biopolymers like poly-lactic acid (PLA), polybutylene adipate terephthalate (PBAT), etc (Al-Itry et al., 2012).

PHAs are an excellent choice for food packaging applications due to their many benefits. These include their biodegradability, renewability, FDA (U.S.A. Food and Drug Administration) approval, and good barrier properties. PHAs are a more environmentally friendly alternative to traditional plastic packaging, as they are compostable and made from renewable resources (Vicente et al., 2023). Moreover, PHAs can be custom formulated to create different packaging types and function similar to conventional plastic. PHAs exhibit good barrier properties toward oxygen, carbon dioxide, and moisture, making them ideal for food packaging applications. Additionally, PHAs can be blended with other biopolymers or fabricated with nanocomposites based on PHA and other organic or inorganic fillers to improve their economic viability and mechanical properties. Lastly, PHAs can be combined with other materials, such as tannins, to create fully bio-based films with multifunctional properties, such as antimicrobial and antioxidant properties, for smart food packaging applications (Koller, 2014).

Overall, PHAs offer numerous advantages for food packaging applications and are a safe and effective choice for those looking to reduce their environmental impact and this why using PHAs for food packaging can help reduce the negative environmental impact of traditional plastic packaging and promote sustainability through reduced waste, reduced carbon footprint, and reduced pollution due to biodegradability (Koller, 2014, Masood, 2017).

3. Research question

The following questions are expected to be answered:

1. What bio-derived polymers demonstrate efficient compatibility with PHAs in blending?
2. Which polymer can be blended with PHAs to demonstrate acceptable mechanical and barrier properties?

4. Purpose and limitations of the work

4.1 Purpose

The main objective of this Master thesis is to develop a polymer blend based on polyhydroxyalkanoate suitable for packaging and produce film packaging material via extrusion and compression molding.

4.2 The limitations of packaging systems

Packaging systems offer numerous advantages, including increased safety, convenience, and theft prevention. However, there are several limitations that businesses must consider (Devlieghere et al., 2004, Ivonkovic et al., 2017).

Limitations include.

- **Cost:** Incorporating packaging can increase production expenses and raise retail prices. The packaging can account for up to 40% of the selling price of products in industries like cosmetics. Developing new packaging can also be expensive, further driving up costs.
- **Environmental impact:** Packaging is a significant contributor to landfill waste. Certain packaging materials, such as plastic, can take hundreds of years to decompose, causing long-term environmental damage.
- **Wasted space:** Packaging can create an illusion of a larger product, resulting in wasted space and increased shipping costs.
- **Fragility:** Some packaging materials, such as glass, are delicate and prone to breakage, resulting in product damage and waste (Devlieghere et al., 2004).
- **Poor barrier properties:** Paper packaging offers less of a barrier to oxygen, light, and microbes than other materials such as plastic.
- **Compromise:** Flexibility in packaging machinery often requires compromising in at least one key area, such as performance, speed, price, changeover time/consistency, footprint, or complexity. Though undesirable, this challenge can be addressed by analyzing these areas and proactively determining the order of compromise (Devlieghere et al., 2004).

Therefore, businesses must carefully weigh the pros and cons of packaging systems and consider these factors when selecting materials and machinery. The food industry is influenced by the limitations of packaging systems which can impact production costs, environmental impact, and product quality. When selecting packaging materials and machinery, food manufacturers consider these factors. It is crucial to balance the need for packaging with environmental concerns, and food companies can achieve this by focusing on sustainability, protecting products, communicating crucial information to consumers, and minimizing the environmental impact of packaging (Ivonkovic et al., 2017). This approach lessens the impact on the environment while ensuring that products reach customers in the best possible shape.

Nonetheless, bio-based packaging poses food safety and regulatory challenges that require further research. These include complying with environmental laws relating to packaging materials and the lack of appropriate infrastructure for the disposal of biodegradable materials (Marsh and Bugusu, 2007).

5.Literature review

5.1 Circular economy and packaging

In the context of sustainable food packaging, the concept of a circular economy refers to a system where packaging materials are reused, recycled, or composted, and kept out of landfills and the environment (COMMISSION, Brussels,16.1.2018). The circular economy is a powerful economic system that focuses on reusing and recycling resources to maximize efficiency and minimize waste. This innovative approach involves designing materials for long-term use, rather than disposal, creating a continuous loop of product and material utilization. The packaging industry is one of the areas where circular economy principles are gaining momentum as companies seek to develop more sustainable solutions (Matthews et al., 2021).

Circular packaging solutions are diverse and include reusable, recyclable, compostable, and minimalist. These options prioritize resource efficiency, environmental impact, cost-effectiveness, and consumer perception. Compared to traditional packaging solutions, which are often designed for one-time use and disposal, circular packaging solutions offer a more sustainable and efficient alternative (Beltran et al., 2021).

By reducing waste and minimizing environmental impact, circular packaging solutions can help address some of the world's most pressing sustainability issues. Companies are making significant progress towards achieving a circular economy of packaging, with the goal of providing high-quality food and drinks in packaging that is 100% circular, low carbon, and preserves materials in use. With continued investment and innovation, circular packaging solutions have the potential to transform the way we consume and dispose of materials, while also promoting a more sustainable and eco-friendly lifestyle (Cruz and Varzakas, 2023).

The circular economy is heavily reliant on government intervention and policy efforts. Various countries, including the European Union and its member states, have taken significant steps towards combating the ever-growing environmental crisis. New laws, regulations, and national strategies have been implemented with the aim of promoting the importance of circular economy in areas such as plastic materials and packaging, recycling, and waste management (Zhu et al., 2022). As a result, it is imperative for packaging designers to remain up to date with

relevant laws, policies, and strategies pertaining to circular economy, plastics, waste management, and packaging. By doing so, they can ensure that their designs are in line with current regulations and contribute towards a sustainable future (Zhu et al., 2022, Schmidt et al., 2021). The European political agenda has placed significant emphasis on the implementation of circular economy requirements for polymers, with a particular focus on polymer packaging. This commitment is fully aligned with the European Green Deal and the UN Sustainable Development goals, which prioritize environmentally sustainable practices (Schmidt et al., 2021).

As part of the EU's Green Deal, the circular economy action plan aims to foster the creation of sustainable products and businesses, while also implementing waste prevention policies. Key product value chains, such as packaging and plastics, have been identified as high priority areas in this regard. To ensure that circular economy principles are met, future legislation will expand the scope of the Eco-design Directive, which will encompass a wider range of products. Consequently, the EU is committed to a more sustainable future, with the aim of creating products that minimize waste and promote environmental protection (Schmidt et al., 2021).

5.2 Eco-Friendly food packaging

Implementing sustainable food packaging solutions is essential to protect customers and ensure food quality, safety, and optimum shelf life. This, in turn, will contribute to the production of future circular food supply chains by relying on eco-friendly packaging (Cruz and Varzakas, 2023, Guillard et al., 2018). We must carefully assess the significance of depleting fossil resources in light of the needs of modern society for food, fuel, energy, and materials (Guillard et al., 2018, Sudesh and Iwata, 2008). The issues of global climate change and fossil fuel depletion have raised alarms among scientists and politicians around the world (Sudesh and Iwata, 2008). Therefore, governments, academia and the industrial sector are making great efforts to find a sustainable solution to the growing energy crisis. However, there is still a lack of effort to create and use sustainable materials in the modern lifestyle (Sudesh and Iwata, 2008).

The plastic issue must be tackled soon to enter the virtuous loop of circular economy and a sustainable plastics economy could deliver considerable benefits. The last ten years have seen a significant increase in interest in bio-based food packaging. This calls for serious reflection on our transition to a circular economy through biodegradable materials (Guillard et al., 2018).

Biopolymers were originally intended for use in packaging, agriculture, and other industries; the limited performance and high cost of biopolymers are major barriers to their deployment as alternatives to conventional non-biodegradable polymers (COMMISSION, Brussels, 16.1.2018). The cost of some biopolymers is higher compared to conventional plastics. This is not only due to the high cost of the raw materials needed to manufacture biopolymers. It is mainly due to the low amount of production. Therefore, it is necessary to develop new applications for polymers to use them in large quantities that are economically feasible. The challenge for optimizing biodegradable polymers lies in the fact that they must remain stable during storage and use, and otherwise degrade after their useful life (Nilsen-Nygaard et al., 2021).

Packaging plays a significant role in every aspect of our daily life, and it has shown continuous increment. In recent years, there has been a growing interest in the use of biomaterials. These are materials that are derived from natural sources and can be naturally degraded over time. This increased attention is due to the depletion of fossil fuels and the pressing need to reduce the amount of waste generated by packaging (Berthet et al., 2015, Cruz and Varzakas, 2023).

In this context polymers that are biodegradable are made to break down naturally through the actions of living organisms. The development of practical processes and products using bio-based polymers like starch, cellulose, lactic acid, PBAT, and PHAs has seen remarkable progress (Nilsen-Nygaard et al., 2021).

However, advancements in technology, research, and policy can help overcome barriers and make the transition to a more sustainable and bio-based economy more feasible. However, if used carefully and contentedly, bio-based materials may be superior in terms of sustainability and environmental protection. The aim of producing bio-based film was to bring the most updated information in the new era of sustainability and food packaging.

5.3 Materials requirement

The functions of food packaging are related to protecting and preserving food products, providing information to consumers, and minimizing environmental impact.

Food packaging requires both barrier properties and good mechanical properties to protect the food from external forces and contaminants. The barrier properties are crucial in food packaging to obstruct the gain or loss of moisture and represent a barrier to avoid or reduce permeation of water vapor, oxygen, carbon dioxide, and other volatile compounds. However, these requirements would be exclusive for the food type to be packed where materials need to

fulfil different requirements in terms of light, moisture, water vapor, and gas barriers (Cruz and Varzakas, 2023).

Nevertheless, the basic properties of packaging materials such as mechanical, optical, and thermal properties must be met first. Therefore, the right food packaging material should ensure the safety and food quality from processing to production and further to handling and preservation before reaching consumers (Al-Itry et al., 2012).

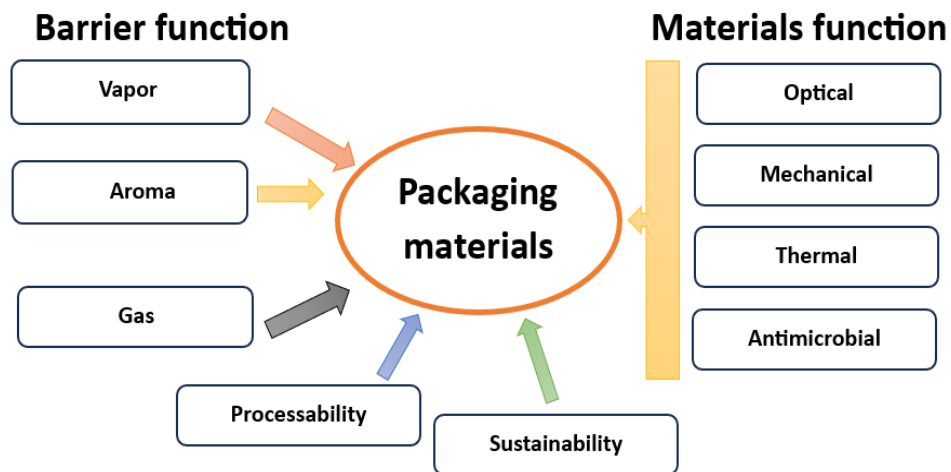


Figure 1: Packaging materials requirements.

In summary, the ability of packaging materials to prevent air and moisture from entering is a critical factor in determining the shelf life of many products. Different types of packaging have different expected shelf lives, and selecting the right packaging materials is essential for maintaining the quality and freshness of the product (Lomate et al., 2018).

5.4 PHAs

Polyhydroxyalkanoates (PHAs) are biodegradable polyesters that bacteria create and store materials inside their cells. PHAs have become popular because they are biodegradable and non-toxic, making them a potential substitute for nonrenewable plastics made from petrochemicals (Poltronieri and Kumar, 2017). They are known for their biocompatibility, and flexible properties. PHAs are made through the fermentation of microorganisms and their physical and chemical properties are dependent on the type of monomer used. The properties of PHAs can vary greatly depending on their composition. PHAs are not soluble in water and are measured by their hydrophobicity, melting point, glass transition temperature, and degree of crystallinity. PHAs have a range of mechanical properties, from hard and crystalline to

elastic. One of the most notable properties of PHAs is their biodegradability (Saravanan et al., 2022).

The synthesis of PHAs is a complex process and can be influenced by several factors such as temperature, pH, and nutrient sources like nitrogen, phosphorus, sulfur, or oxygen. However, the availability of commercially produced PHAs is low due to high production costs and limited yields (Bugnicourt et al., 2014). PHAs are mainly found as insoluble particles within microorganisms in the cytoplasm; when there is an imbalance of nutrients, caused by an excess of carbon sources or a deficiency of nutrient sources, the intracellular enzymatic system produces high molecular weight PHAs by transferring carbon sources. PHAs have enormous potential for large-scale production since they can be easily transformed into various forms with different properties. They have been utilized in various technological fields, including medical applications, adhesive production, filmmaking, molded goods, paper coatings, packaging, non-woven fabrics, and performance additives (Saravanan et al., 2022).

There are different types of PHAs based on the composition of their monomers and the number of carbon atoms in the units. The classes of PHAs are as follows:

- Short-chain length PHAs (scl-PHAs): These PHAs have 3 to 5 carbon atoms in their units.
- Medium-chain length PHAs (mcl-PHAs): These PHAs have 6 to 14 carbon atoms in their units.
- Long-chain length PHAs (lcl-PHAs): These PHAs have more than 14 carbon atoms in their units (Saravanan et al., 2022).

Apart from this classification, PHAs can also be categorized based on their chemical structure, such as homo- or copolyester, and the type of hydroxy fatty acids they contain. There are many benefits to using PHAs over other biodegradable plastics.

Here are some advantages of PHAs:

- Biodegradability: PHAs can be broken down by microorganisms in the environment, which helps to reduce pollution and waste.
- Durability: PHAs are strong and sturdy, with properties similar to conventional plastics. This makes them suitable for many different uses.
- Versatility: PHAs can be produced with different compositions, which means they can be tailored to specific applications.

- **Biocompatibility:** PHAs are safe to use in medical applications and won't cause harm to the body.
- **Renewable:** PHAs are made from renewable resources, such as plant-based materials. This helps to reduce our dependence on fossil fuels.
- **Reduction of microplastic pollution:** PHAs have been suggested as an alternative to conventional plastics to combat microplastic pollution.

Although PHAs have some drawbacks, such as higher production costs and limited thermo-mechanical stability, their advantages make them a promising alternative to other biodegradable plastics (Acharjee et al., 2023). PHBV, a specific type of PHA, is ideal for coated paper and films as it has remarkable gas barrier properties. Furthermore, PHAs can be blended with other polymers to create innovative applications in food packaging. PHA nanocomposites, which are manufactured using nanosized fillers, have become competitive in the food packaging market. However, due to the high production costs and low production yields, PHAs are not widely available commercially (Meereboer et al., 2020).

PHAs currently have a wide variety of uses in many fields. Here are a few examples:

- **Coating Agent:** PHAs can be used as a coating agent because of their ability to form a film. This makes them useful for protecting surfaces and improving their durability (Wang et al., 2014, Reddy et al., 2003).
- **Medical Devices:** PHAs are used to create medical devices like surgical sutures, implants, and drug delivery systems. PHAs are biocompatible and can break down in the body, which means less need for additional surgeries to remove them (Reddy et al., 2003).
- **Agriculture:** PHAs can be used in agriculture for things like biodegradable mulch films, seed coatings, and controlled-release fertilizers. This makes them an eco-friendly alternative to conventional plastic materials (Reddy et al., 2003).
- **Nanotechnology:** PHAs have a variety of uses in nanotechnology, especially as PHA nanoparticles. These nanoparticles can be used for things like drug delivery, imaging, and tissue engineering (Reddy et al., 2003).
- **Blends and Composites:** PHAs can be mixed with other materials like starch, lignin, and cellulose derivatives to improve their properties. Blends and composites made from PHAs have improved stability, elasticity, and decreased oxygen permeability (Kumar et al., 2021). Because it is a natural and non-toxic polymer, it can be used in a wide range of applications like food packaging. PHAs are available on a global market in

grades for film and injection molding as well as grades for extrusion and blow molding.(Wang et al., 2014)

- Nanobiotechnology: PHAs can be used to create micro- and nanostructures on solid surfaces for use in nanobiotechnology. This includes developing biosensors, bioelectronics, and nanodevices (Poltronieri and Kumar, 2017, Kumar et al., 2021).

It's important to note that optimizing, extracting, and characterizing PHAs are crucial steps in their production and use. Various techniques like solvent extraction, digestion methods, microscopy, spectroscopy, and chromatography are used for these purposes.(Poltronieri and Kumar, 2017)

Overall, PHAs have a wide range of uses and offer a promising solution for sustainable and eco-friendly materials in many industries. The PHAs-based plastics are biodegradable, and many different genus and species of bacteria and fungi can completely biodegrade them within a year in both aerobic and anaerobic conditions (Reddy et al., 2003). When the PHAs are biodegraded in aerobic conditions, carbon dioxide and water are produced, Figure 2 shows PHAs structure (Muthusamy and Pramasivam, 2019)

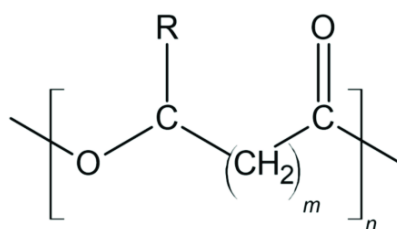


Figure 2: PHAs Structure (Gomes Gradissimo et al., 2020)

The mechanical properties and biocompatibility of PHA can be changed by blending, modifying the surface or combining PHA with other polymers, enzymes and inorganic materials, making it possible for a wider range of applications (Kumar et al., 2021). In contrast to other bio-based plastics made from polymers like polylactic acid, the polymer can withstand temperatures up to 180 °C and show a low permeation of water. They are also UV stable. The crystallinity may range from a few to seventy percent. A material with a higher percentage of valerate improves its processability, impact strength, and flexibility. Halogenated solvents like chloroform, dichloromethane, and dichloroethane dissolve PHAs (Le Delliou et al., 2023).

The unique barrier properties of PHAs make them a great option for producing bottles for liquid foods and CO₂-containing liquids. Additionally, PHAs' high UV-barrier is

particularly beneficial for protecting unsaturated lipid components in food from the formation of radicals, which can accelerate spoilage. Furthermore, it is worth noting that the biodegradability and non-toxicity of PHAs could make it a better alternative to other polymers for food packaging. In addition, PHAs packaging can be composted after use, which makes it a practical and eco-friendly option (Tan et al., 2014).

5.5 PHBV

PHBV can be created by using bacterial fermentation to convert renewable resources like sugars and lipids. By adjusting the fermentation conditions, the ratio of 3-hydroxybutyrate (3HB) to 3-hydroxyvalerate (3HV) in the copolymer can be controlled. One way to enhance the processability of PHB is to combine it with 3-hydroxyvalerate (HV) through bacterial fermentation or synthetic methods.

(PHBV) is a thermoplastic copolymer with excellent properties and potential uses in several areas. PHBV has a melting point of approximately 153 °C and a glass transition temperature of −1 °C, causing it to behave like rubber at room temperature (Policastro et al., 2021). It is unstable above 160 °C during melt processing, which limits its practical uses as a commodity material. The ratio of 3HB to 3HV affects the material's properties, such as its crystallinity, melting point, and degradation rate. PHBV can be processed using various methods, such as injection molding, foil blowing, and thermoforming. Electrospinning is a promising method for producing PHBV fibers for tissue engineering and other biomedical applications. PHBV has potential applications in various fields, including packaging, agriculture, and biomedical engineering. In biomedical engineering, PHBV has been used for drug delivery, tissue engineering, and wound healing. PHBV-based materials have also been developed for use in 3D printing and as coatings for medical devices. However, it's still not widely used because it's expensive to produce and doesn't have a high productivity rate. Researchers are working to find ways to make PHBV production more efficient and cost-effective (Policastro et al., 2021, Rivera-Briso and Serrano-Aroca, 2018).

PHBV is a versatile material with exceptional biocompatibility and biodegradability properties. The properties of PHBV make it an ideal candidate for biomaterial applications, such as cardiovascular stents, drug release systems, and medical packaging. In the field of tissue engineering, it can be used to create tissue patches, biodegradable implants, and porous

scaffolds that allow for the treatment of bone defects (Policastro et al., 2021). PHBV also has a wide range of applications in other industries, including everyday disposable objects, high mechanical resistance products, and denitrification systems for wastewater treatment. However, the high production cost of PHBV limits its use, and research is focused on finding new microbial strains for higher PHBV accumulation, developing more efficient fermentative routes, and reducing polymer extraction costs (Policastro et al., 2021).

Figure 3 shows the PHBV structure. Thermoplastic polymer PHBV is brittle, has low impact resistance, and has low elongation at break. PHBV breaks down into carbon dioxide and water when it is disposed of and broken down by bacteria as microorganisms use PHBV, like fats do for humans, as a source of energy. The PHBV cleavage occurs by elimination reaction at the ester bond, and the enzymes that they produce degrade it and consume it. It can be used in medical applications because hydrolytic degradation occurs slowly (Kennouche et al., 2016, Le Delliou et al., 2023).

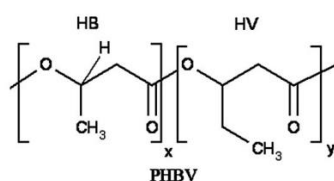


Figure 3: PHBV structure (Boufarguine et al., 2013)

PHBV is a type of biodegradable polymer that's not easy to turn into films due to a few issues. Thermal degradation is one of them, which can occur while processing PHBV and affect the quality of the films. PHBV is also a brittle and stiff material, which makes it harder to turn into films with good mechanical properties. The low melt strength of PHBV makes it tough to use film-blowing techniques. Also, PHBV is difficult to crystallize before releasing pressure, which can impact its foaming performance (Muthusamy and Pramasivam, 2019). Despite these obstacles, there are some ways to improve the processing of PHBV. For instance, blending PHBV with other polymers or additives can enhance its mechanical and barrier properties. In addition, optimizing the processing conditions like temperature, pressure, and extrusion rate can also improve the quality of PHBV films.(Le Delliou et al., 2023)

PHBV is superior to other bioplastics in terms of environmental, thermal, and mechanical properties. However, its high cost and low productivity pose challenges that need to be addressed. Many studies have been conducted to modify PHBV chemically and physically, including combining it with other materials such as natural fibers, carbon nanomaterials, and nanocellulose. These efforts have resulted in the creation of a range of composite biomaterials with increased potential applications (Rivera-Briso and Serrano-Aroca, 2018, Policastro et al., 2021). PHBV has great potential to replace petroleum-based polymers due to its biodegradable and biocompatible properties. However, it has limitations in areas such as mechanical strength, water absorption, and thermal properties, which restrict its applications. Researchers worldwide are working hard to overcome these challenges and improve the material (Rivera-Briso and Serrano-Aroca, 2018). It's crucial to note that PHBV exhibits a high oxygen barrier, also known as a low oxygen transmission rate (OTR). This is necessary to prevent the growth of aerobic microbes and the oxidative spoilage of unsaturated fatty acids in the food.

Despite the progress made, there is still a need for further research to find new enhancement strategies and produce advanced PHBV-based materials that can overcome these challenges.

5.6 PLA

Poly(lactic acid) (PLA), also known as polylactide plastic, is the most widely used bioplastic currently available. PLA is a type of aliphatic polyester that can be synthesized from renewable resources like corn, and it is highly regarded for its biodegradability, which makes it a popular choice in many industries, including the biomedical field. PLA can be synthesized using different methods, including direct condensation polymerization, azeotropic dehydration condensation, and lactide ring-opening polymerization. Direct condensation polymerization is a low-cost method that requires coupling agents and esterification accelerators. Figure 4 shows the PLA structure.

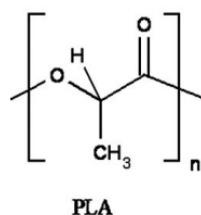


Figure 4: PLA structure (Boufarguine et al., 2013)

It's a versatile material designed to replace traditional petroleum-based plastics in many commercial applications, such as PET. It's even made its way into the medical industry, where it's used to create implants like pins, screws, plates, and rods that break down into lactic acid over time. (Taib et al., 2023).

The primary advantages include PLA plastics' superior performance in conventional plastics manufacturing industry equipment in addition to their high level of rigidity, stability, transparency (Taib et al., 2023). PLA has excellent mechanical and thermodynamic properties. Adding inorganic additives, such as silica nanoparticles, can further enhance its performance. The solubility of PLA is an important factor that affects its manufacturing and processing characteristics. Understanding the material properties of PLA is crucial when choosing the right processing method. PLA can be processed using various techniques, including extrusion, injection molding, and 3D printing. PLA plastics are mostly used in food packaging due to similarities to polyethylene and polypropylene. Additionally, the production of fossil based plastics requires twice as much energy as that of this PLA plastic (Taib et al., 2023). PLA plastics also produce nearly 70% fewer greenhouse gases than conventional plastics when degraded in a landfill. For use in the production of film, molded parts, drinks containers, cups, bottles, and other common household items, PLA and PLA-blends are currently available in granulated form in a variety of grades (Taib et al., 2023).

PLA has a wide range of applications across different industries, from packaging, textiles, and automotive parts to medical devices. In the biomedical field, modified PLA is used for drug delivery systems, tissue engineering scaffolds, and implants (Nampoothiri et al., 2010). PLA is also compostable, which means it can break down into natural elements in a composting environment, making it a more sustainable alternative to non-biodegradable plastics, especially for single-use applications. It is also easier to work with and requires less energy for transformation due to its lower melting point compared to many fossil-based plastics. PLA does not emit toxic fumes when incinerated, making it a safer option for waste disposal. It can be used in a variety of applications and is commonly used in food packaging. PLA behaves better than many tougher plastics and does not emit fumes or bad odors, making it a more pleasant material to work with and use (Farah et al., 2016) .

PLA has higher permeability to moisture and oxygen compared to other plastics, which can be useful in certain applications where controlled permeability is desired. Overall, PLA offers several advantages over other plastics, making it a more sustainable and environmentally

friendly choice for various industries and applications (Farah et al., 2016, Nampoothiri et al., 2010). Lastly, while PLA is compostable, it may not compost fast enough for industrial composters, limiting its usefulness in specific waste management systems. Therefore, when choosing the appropriate material for a specific application, it's essential to consider PLA's higher price, lower durability, higher permeability, and slower composting speed (Ramezani Dana and Ebrahimi, 2023).

On the other hand, PLA's permeability can be an advantage in certain applications where higher permeability is necessary, such as controlled-release drug delivery systems. In terms of mass transfer properties, PLA generally exhibits moderate permeability values for oxygen and carbon dioxide, which are higher than those of some other plastics such as PHBV, PVDC, EVOH, PET, and PVOH. Ultimately, the decision to use PLA should be based on the specific application and its requirements (Singha and Hedenqvist, 2020).

There are several methods to improve the barrier properties of PLA. Here are some of the most common methods:

- Plasma surface treatment: Plasma surface treatment is one of the most effective methods for improving barrier qualities without affecting the substrate's bulk. This method involves exposing the PLA surface to N₂ plasma, which modifies the surface properties and improves the barrier properties (Singha and Hedenqvist, 2020).
- Molecular orientation: Another common way to improve the barrier properties of polymeric materials is through molecular orientation. This involves stretching the polymer to align the polymer chains, which reduces the permeability of gases and liquids.
- Incorporation of additives: The addition of inorganic additives, such as silica nanoparticles or oxygen scavengers, can enhance the barrier properties of PLA. These additives can reduce the permeability of gases and liquids and improve the mechanical properties of the material (Singha and Hedenqvist, 2020).

One of the biggest challenges in widely adopting bio-based polymers is achieving comparable mechanical and barrier properties to synthetic polymers while maintaining biodegradability. PLA is a plastic material that has its advantages and disadvantages, for instance the cost of PLA is a major concern, as well as the need to address various issues related to biotechnological production of lactic acid. These issues include developing high-performance microorganisms that produce lactic acid and reducing the costs associated with raw materials and fermentation processes. Improving biotechnological processes for producing lactic acid from inexpensive raw materials is important to make them competitive with

chemically derived polymers. On one hand, it is more expensive than other plastics that originate from fossil resources, which may not be ideal for cost-sensitive applications. Additionally, PLA is not as long-lasting as some fossil-based plastics (Nampoothiri et al., 2010).

The properties of PLA can be modified by blending it with other polymers or adding plasticizers. To produce PLA packaging, crops like sugarcane or corn are grown and broken down into starch or sugar, protein, and fiber. The sugar or starch is then fermented to produce lactic acid, which is turned into polylactic acid (Nampoothiri et al., 2010). Sometimes, PLA is combined with other materials, like PBAT, to create compostable packaging. However, its inherent brittleness has been a major hindrance to large-scale use. To improve its toughness, several methods have been tried, such as block copolymerization, blending with tougher plastics, and rubber toughening. Unfortunately, these approaches often result in significant decreases in strength and modulus. Therefore, a PLA-based material that has a good balance of stiffness and toughness, along with a high bio-based content, remains elusive (Taib et al., 2023).

Finally its noteworthy to mention one of the common limitations of PLA is its poor thermal resistance, which prevents wider industrial applications, such as in packaging. For instance, PLA products are sensitive to heat and are only suitable for cold dishes and drinks up to 40 degrees Celsius. Furthermore, it's important to note that PLA packaging should not be recycled like other plastics. Proper disposal in an industrial composting facility that provides the necessary conditions is required for it to decompose into natural components. To prevent contamination of the recycling process, it's crucial to dispose of PLA packaging correctly (Guillard et al., 2018).

5.7 PBAT

PBAT is an exceptional eco-friendly copolymer that demonstrates full biodegradability when properly composted. This innovative material is composed of 1,4-butanediol, adipic acid, and terephthalic acid, which, when combined, create a highly stable and mechanically sound product due to the terephthalate portions (Jian et al., 2020). The water-resistant properties of PBAT make it an ideal candidate for use in both marine and freshwater applications. PBAT can be processed through conventional methods such as extrusion, injection molding, and blow molding, and it can be blended with other polymers like PLA and polybutylene succinate (PBS) (Wang et al., 2022) .

PBAT-based nanocomposites have also been explored for industrial and medical applications. Furthermore, PBAT films can be further enhanced with organ montmorillonite, which improves their water vapor barrier properties. The synthesis, characteristics, processing, and application of PBAT are all crucial factors that contribute to a more sustainable and environmentally friendly future (Jian et al., 2020, Wang et al., 2022).

When it comes to selecting materials for various applications, it's crucial to consider the properties of PBAT. Of particular importance are its mechanical characteristics, which can help determine its suitability for different purposes. For instance, PBAT boasts a tensile strength of 21 MPa, which is like that of low-density polyethylene, thanks to the presence of an aromatic ring in its polymer chain (Jian et al., 2020). Additionally, PBAT has a higher elongation at break of 670%, which sets it apart from other polymers like PLA.

PBAT is a type of biodegradable random copolymer that has outstanding mechanical properties, especially when compared to other biodegradable polymers. It is usually marketed as a fully biodegradable substitute for low-density polyethylene and breaks down entirely when composted due to the presence of butylene adipate groups. The high stability and mechanical properties of PBAT come from the terephthalate portions. PBAT is classified as a random copolymer because of its random structure, which means that it cannot crystallize to any significant degree due to the absence of any regular repeating structure. Its outstanding mechanical strength makes it a popular choice for various applications, Figure 5 shows the PBAT structure (Jian et al., 2020).

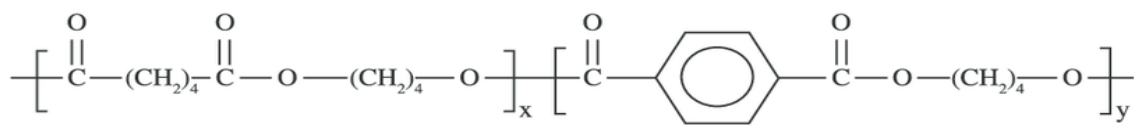


Figure 5: PBAT structure (Nobrega et al., 2012)

PBAT is a promising material in the food packaging industry due to its biodegradability and compostability. Here are some of the advantages and disadvantages of using PBAT in food packaging:

Advantages:

- Compostable: PBAT can break down into natural elements without harming the environment.

- Flexible: PBAT is flexible and has good moisture resistance, making it ideal for packaging food items like fruit and vegetable bags, snack bags, and other flexible packaging applications.
- Sustainable: PBAT is eco-friendly and can replace traditional petroleum-based plastics.(Sciancalepore et al., 2022)

Disadvantages:

- Poor performance: PBAT's performance is limited compared to commonly used polymers, which restricts its applications. The limitations in PBAT's performance compared to commonly used polymers can restrict its suitability for certain applications, especially those requiring superior mechanical strength, heat resistance, or durability.
- Cost: The cost of PBAT is somewhat higher than that of traditional petroleum-based plastics (Sciancalepore et al., 2022).

One of the main disadvantages of PBAT is its slow crystallization rate, which can have a significant impact on its processing and production efficiency. This results in longer production times and increased costs, which may not be ideal for businesses seeking to accelerate their production processes (Kanwal et al., 2022). Researchers are working on developing eco-sustainable blown films with improved performance suitable for flexible packaging applications requiring high ductility. They are also exploring the use of PBAT-lignin-tannic acid composite film as a potential barrier application in food packaging. Moreover, PBAT can be melt-processed on standard polyolefin equipment and can mainly be used in film applications like organic waste bags (Sciancalepore et al., 2022). This makes it possible to create blended copolymers that can replace traditional plastics with materials that are safe for the environment and biodegrade quickly and harmlessly. The main benefit of employing PBAT as a flexible complement to other polymers is that it will maintain biodegradability. The terephthalate components give the materials their excellent stability and mechanical properties (Ferreira et al., 2019).

5.8 Polymer blends

The history of polymer blends is closely related to that of polymers themselves. Blending two or more polymers can create new polymeric systems with unique properties, eliminating the need for synthesizing new polymers (Dorigato, 2021). However, blending different polymers often results in immiscible and incompatible blends, displaying a coarse

morphology (Muthuraj et al., 2018). Thus, a compatibilization process is necessary to modify the interfacial properties and reduce the interfacial tension coefficient for the desired morphology. Compatibilizers, including nanoparticles, have been used to modify the final morphology of polymer blends.(Muthuraj et al., 2018)

Polymer blends involve the combination of two or more distinct polymers in order to create a material that exhibits a specific set of properties. The way in which these blends flow and deform under stress is largely influenced by their thermodynamics, morphology, and processing, which are all critical factors to consider when examining their behavior. Understanding the rheology of polymer blends is thus essential for gaining a complete understanding of their characteristics and applications (Manson, 2012).

The flow behavior of polymer blends can be affected by interactions between different polymers, which can result in phase separation. Polymer blends are categorized as either thermodynamically miscible or immiscible, with immiscible blends exhibiting phase separation and miscible blends being well-mixed at the molecular level (Koning et al., 1998, Manson, 2012). The behavior of polymer blends can change with flow, affecting their microstructure and flow properties. Understanding polymer blend rheology is crucial for applications such as processing, design, and development. Blending polymers is a cost-effective way to create new materials with superior properties (Koning et al., 1998). Polymer blending typically occurs in processing machines, such as extruders, which are considered standard industrial equipment. Polymer blends offer limited financial risk when developing new materials, and a wide range of material properties are achievable by adjusting the blend composition (Koning et al., 1998).

5.9 PHBV, PLA, PBAT blends

Blending PHBV, a biodegradable polyester, with PLA, a thermoplastic made from renewable resources, results in a material with enhanced properties suitable for a wide range of applications (Hernández-García et al., 2022). These blends are suitable for use in agriculture, packaging, textiles, and biomedical industries due to their improved mechanical properties and biodegradability. Compared to non-biodegradable plastics, PHBV-PLA blends offer a sustainable option that can help reduce waste and lower carbon footprint (Berthet et al., 2015, Javadi et al., 2010). Using PHBV-PLA blends in various industries provides environmental benefits such as utilizing renewable resources, reducing waste, and contributing to closed-loop systems. Additionally, these blends can be composted and used as a nutrient-rich soil amendment, further reducing waste, and promoting sustainable plastic materials (Mofokeng and Luyt, 2015).

The applications for PHBV-PLA blends are extensive and diverse, with specific uses depending on blend composition, processing method, and additives used. However, one thing is certain: PHBV-PLA blends offer a promising solution for creating a more sustainable and environmentally friendly approach to plastic materials. Overall, blending PHBV with PLA can lead to improved mechanical properties, such as increased modulus, tensile strength, and elongation at break, as well as improved crystallization and other physical properties. However, the specific effects will depend on the blend ratio, processing conditions, and other factors (Kennouche et al., 2016, Berthet et al., 2015).

Blending PHBV and PBAT can result in a mixture that possesses impressive ductility and improved properties. PBAT is a suitable choice for film extrusion due to its high thermal stability, ductile behavior, and good melt processability (Javadi et al., 2010). However, compatibilizers are required to produce miscible blends with PHA since PBAT is not compatible with any of the PHAs. Adding natural fibers that have been organically modified, clay, and other compatibilizers are preferred methods for enhancing compatibility. (Pan et al., 2016) Numerous studies have been conducted to examine the properties of PHBV/PBAT blends. The blend has been observed to improve impact strength and elongation at break, but the tensile strength has decreased. However, the specific effects will depend on the blend ratio, processing conditions, and other factors (Pan et al., 2016). Blends of PHBV and PBAT have shown great potential in the field of packaging. These blends can be used to produce nanocomposite films, which have been extensively studied for their mechanical, thermal, and barrier properties. Both PHBV and PBAT are biodegradable polymers, making them the perfect choice for environmentally friendly packaging applications (Pan et al., 2016, Berthet et al., 2015).

In conclusion, blending PHBV and PBAT has the potential to create materials with improved properties and biodegradability, making them suitable for various industrial applications. The PHBV/PBAT blend has numerous applications, including packaging, where it has demonstrated potential in mechanical, thermal, and barrier properties. Overall, PHBV/PBAT blends offer a range of benefits, including enhanced properties and biodegradability, making them ideal for various packaging applications (Xiao et al., 2009).

6. Description of methods

6.1 Modification of PHAs

Modifications of PHAs shown in Figure 6. Blending two or more polymers is a practical and economical way to develop new materials with unique properties such as thermal and mechanical (Sharma et al., 2021).

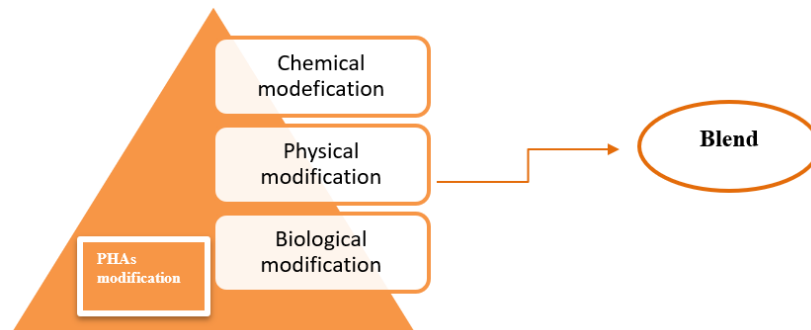


Figure 6: Physical modification through blending will be used in our current project.

6.2 Physical Modification of PHAs

The blending strategy and the addition of additives are widely used approaches to modify the deficiencies of individual polymers. In addition, blending is more cost-effective than co-polymerization and other chemical modification procedures; biodegradable polymer blends and composites are created with the intention of achieving the desired phase morphology and enhanced performance through the improvement of adhesion, reduction of interfacial tension (Kumar et al., 2021). However, the blending with various polymers is restricted by three factors: the biphasic system's morphology, degree of miscibility, and compatibility between phases (Sharma et al., 2021). The amorphous mixture of two polymers forms a single phase at thermodynamic equilibrium. As a result, the blend is considered compatible, enhancing the blend polymer's mechanical and physical properties that are suitable for use in packaging films (Poltronieri and Kumar, 2017, Sharma et al., 2021).

The kind of food and the product's shelf life play a significant role in determining which plastic packaging materials are used for food packaging. The plastic film materials that are intended for use in food packaging need to be adaptable enough to withstand the handling process, as well as able to preserve the food products' aroma and keep them fresh. Stereoregular poly (L-lactic acid) [PLLA], for instance, cannot handle beverages that are heated at high temperatures (Kumar et al., 2021). Stereo complex PLA, on the other hand, may be resistant to

high temperatures and suitable for high-temperature beverage applications. Specific grades of PHA with a high degree of crystallinity can provide better barrier properties than PLA while PLA alone does not provide good gas and moisture barrier properties. To produce products comparable to those made from polymers derived from fossil fuels, biodegradable polymer blends are therefore desirable (Poltronieri and Kumar, 2017, Kanda et al., 2018).

6.3 Blending

PHBV blended with PLA and PBAT in various ratios as shown in Figure 7 were used in this study.

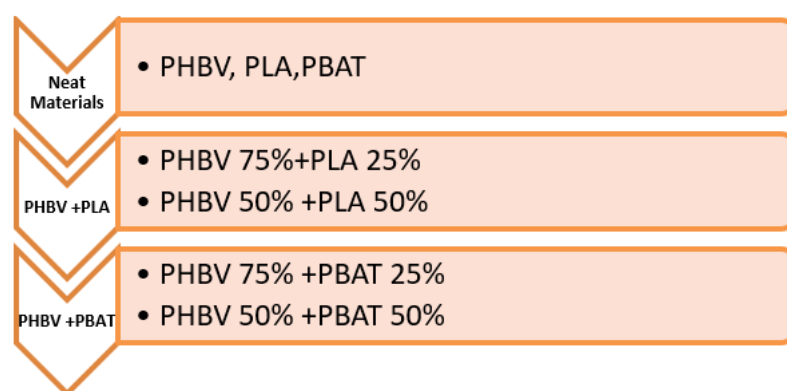


Figure 7: Polymer blending

6.3.1 Twin-screw extruder

As shown in Figure 8, the Thermo Fisher Process 11 Extruder has been used to extrude the materials, blends containing PHBV and PLA in the ratio of 75/25, 50/50. In addition to that, blend containing PHBV and PBAT with the ratio of 75/25, 50/50 considered. The samples were melted and extruded using a twin-screw extruder at a barrel temperature of 190 – 200 °C and a rotation speed of 125 rpm, and then the extrudate used to make pellets. 750 grams of each combination was extruded. Pelletizer was used to obtain specified pellet lengths and diameters from filaments. The pellets were then injection molded.



Figure 8:Thermo Fisher Process 11 Extruder

6.3.2 Injection molding

Minijet Pro Injection Molding has been used to mold test specimens according to standards. Neat materials (PHBV, PLA and PBAT) and different blends were dried in a convection oven at 70°C for at least 24 h before processing and later stored in airtight bags. The following parameters were used in the molding process: cylinder temperature of 200°C, mold temperature of 60°C, pressure of 300 Pa, and a time of 15 seconds. For all blends except PLA, the post pressure time was set at 60 seconds, while for PLA, it was extended to 3 minutes. The mold type used was in accordance with industry standards. A total of 175 dog-bone specimens were produced from different combinations for tensile testing, as illustrated in Figure 9.

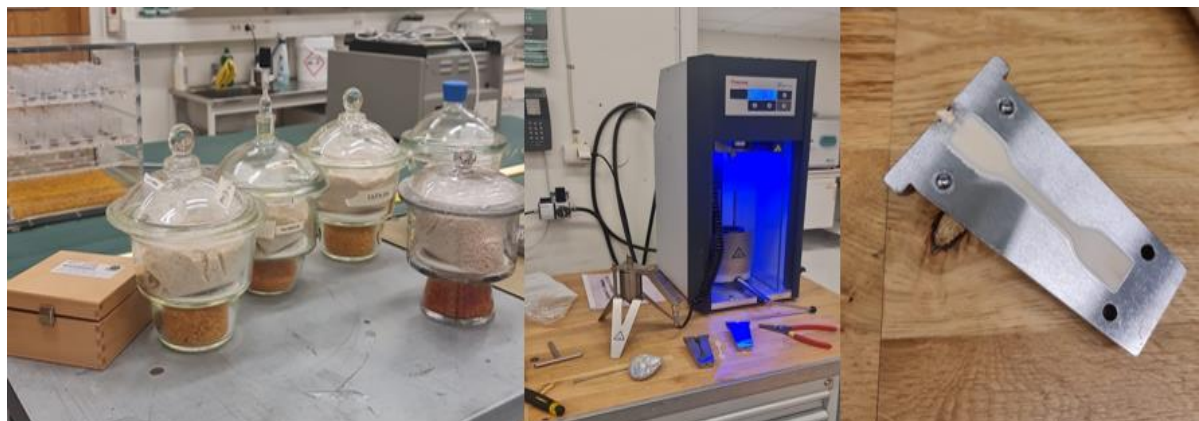


Figure 9:Injection moulding

6.3.3 Film extrusion

Thermo Fisher Process 11 Extruder twin screw has been attached with a film extruder and film die and was used for fabricating films from the blended materials. The films were fabricated at same parameters of materials extruded, all zones were set at 190 °C, 50 rpm speed and extruded onto a chill roll set, as shown in Figure 10.



Figure 10: conveyor belt section.

6.3.4 Compression molding

The films were prepared by compression molding in a polymer ratio of 75:25 PHBV: PLA, 50:50 PHBV: PLA, 75:25 PHBV: PBAT, 50:50 PHBV: PBAT, and neat PHBV, neat PLA, and neat PBAT. The pelletized blends were dried in a convection oven at 70 °C for 24 h prior to compression molding, 70 films were prepared by placing four grams of pellets onto Teflon sheets in a hot mold, and then compressing them at precisely 200 °C for four minutes at 20 & 40 bars, as it's shown in Figure 11.



Figure 11: Compression moulding

7. Characterization

7.1 Tensile test

A fundamental test in materials science and engineering is tensile testing, also known as tension testing, in which a sample is subjected to controlled tension until failure. Through a tensile test, properties like ultimate tensile strength, breaking strength, maximum elongation, and reduction in area can be directly measured (Zheng et al., 2020). The following properties can also be determined from these measurements: yield strength, Young's modulus, Poisson's ratio, and strain-hardening properties. The most common method for determining the mechanical properties of isotropic materials is uniaxial tensile testing. Biaxial tensile testing is used on some materials. The primary difference between these testing machines is how the load is applied to the materials. (Davis, 2004, Zheng et al., 2020)

Tensile test was performed on the Tinius Olsen H10KT universal testing machine (UTM) equipped. The parameters were as below:

- The modulus was determined at 1 mm/min using a load cell of 1000 N and stop it at 250 N.
- The tensile strength was determined at 10 mm/min using a load cell of 5000 N.

The tests were repeated 10 times for each batch. Properties such as tensile strength, young's modulus, and strain-at-break were measured.

7.2 Differential Scanning Calorimeter (DSC)

A thermal analytical method known as differential scanning calorimetry (DSC) measures the temperature-dependent variation in the amount of heat required to raise a sample's

temperature from that of a reference. Throughout the duration of the experiment, the temperature of the sample and the reference is nearly identical. For the most part, a DSC analysis's temperature program is set up so that the temperature of the sample holder rises linearly over time. Over the temperature range that will be scanned, the reference sample should have a well-defined heat capacity (Kennouche et al., 2016, Schick, 2009, Menczel et al., 2009). Tests were performed on neat polymers and all blends in an inert atmosphere using nitrogen. The tests were repeated three times for each batch. The test temperature was between -40 and 200°C.

The degree of crystallinity of the neat materials was calculated by the following equation.

$$X_c(\%) = \frac{\Delta H_m}{\Delta H} \times 100$$

Because of the cold crystallinity of PLA, the degree of crystallinity of neat PLA was calculated by the following equation.

$$X_c(\%) = \frac{\Delta H_m - \Delta H_c}{\Delta H} \times 100$$

The degree of crystallinity of the blend was calculated by the following equation.

$$X_c(\%) = \frac{\Delta H_m}{\Delta H \times W(\%)} \times 100$$

7.3 Fourier Transform Infrared Spectroscopy (FT-IR)

Tests performed in absorption mode in the transmission range of 4000 cm⁻¹ to 400 cm⁻¹; the spectra were recorded at 64 scans and 4 cm⁻¹ band resolution. A method for obtaining an infrared spectrum of a solid, liquid, or gas's absorption or emission is called "Fourier-transform infrared spectroscopy" (FTIR). Over a broad spectral range, an FTIR spectrometer simultaneously collects high-resolution spectral data. A dispersive spectrometer, on the other hand, measures intensity over a limited number of wavelengths at once, so this provides a significant advantage (Kennouche et al., 2016, Petit and Puskar, 2018). FTIR was used to characterize the PHBV, PLA, PBAT and the blends to investigate the reaction connection between the PHBV and other blends.

7.4 Thermal gravimetric analysis (TGA)

Thermo-analytical technique TGA measures the sample's mass over time while temperature changes. It provides information regarding thermal decomposition, thermal stability, phase transitions, chemisorption, absorption, and desorption (Saadatkah et al., 2020). TGA gives a clear image of the composition of the analyte, the major focus is to measure how much weight is gained or lost, at a constant heating rate. By keeping track of the percentage weight loss of the cured sample, one measures the thermal resistance of the sample (Zembouai et al., 2014).

TGA was conducted using a TGA Q500 (TA Instruments) to determine the thermal stability of the control samples and blends. A heat ramp was used from 30 °C to 500 °C, performing tests in an inert atmosphere using nitrogen. The tests were repeated three times for each batch. Weight loss and maximum degradation percentage were obtained by graphical means. The average of two runs was taken for analysis.

7.5 Oxygen and water vapor barrier (WVTR)

Water vapor permeability (WVP) was gravimetrically determined, using anhydrous calcium chloride inside the permeation cells to promote water vapor diffusion through the bioplastic, at 23 °C and 50% relative humidity for 7 days. Each measurement was performed on at least 5 independent replicates.

Testing the water vapor permeability of materials is a critical process that measures their ability to allow water vapor to pass through them over a specific period. This test is also known as moisture vapor transmission rate (MVTR) or water vapor transmission rate (WVTR) (Al-Gharrawi et al., 2022). To conduct this test, a specific area is measured to determine the mass of water vapor that can permeate it while maintaining a constant temperature and humidity. (Trinh et al., 2023) This test plays a crucial role in the packaging industry as it helps prevent moisture damage to products. It is also used in construction to determine the effectiveness of building materials in protecting against moisture damage. (Trinh et al., 2023)

The WVTR analysis is essential in determining a material's ability to withstand moisture, also known as its barrier effect. This test is particularly important in developing materials that need to endure varying moisture levels at different temperatures, such as food packaging, construction materials, and medical equipment (Higgs et al., 2014, Al-Gharrawi et al., 2022). During the test, the amount of water vapor that penetrates a substance or surface over a specific duration is measured in grams per square meter per day (g/m² per day). This

measurement serves as the standard for comparing films' ability to resist moisture transmission, with lower values indicating better moisture protection. The test is conducted at a selected temperature and humidity level, and the data is reported in g/m² per day (Higgs et al., 2014).

Additionally, WVTR analysis is employed to determine the moisture-barrier properties of pharmaceutical packaging. This is crucial since a high percentage of Active Pharmaceutical Ingredients (APIs) are sensitive to moisture. WVTR Permeation Analysers are specialized equipment used to conduct this test. The test specimen is mounted on a test dish, and a barrier film is sealed between a wet chamber and a dry chamber. A pressure modulated sensor measures the amount of moisture transmitted through the material being tested (Al-Gharrawi et al., 2022).

8. Results and Discussion

8.1 Tensile test

Mechanical properties such as tensile strength, young's modulus, and strain-at-break were measured, and these properties of the blends are presented below. The crystalline nature of PHBV and the PLA's semi-crystalline polymer nature result in them exhibiting high stiffness and tensile strength, while PHBV showed poor elongation at break. PBAT showed dissimilar properties to this, with a very low stiffness modulus of 78.9 MPa and tensile elongation 419 %. Summary of tensile properties: the tensile strength, Young's modulus, and elongation-at-break values of neat materials and blends shown in Table 1 and Table 2.

Table 1: Tensile properties

Sample ID	Ultimate strength (MPa)		Elongation at break (%)	
	Average	SD	Average	SD
Neat PHBV	33.65	7.12	2.75	0.613
Neat PLA	56.94	6.58	7.23	0.967
Neat PBAT	18.64	1.99	419.3	100.8
PHBV 50%: PLA 50%	41.06	2.04	5.17	0.952
PHBV 75%: PLA 25%	35.03	5.7	2.63	0.679
PHBV 50%: PBAT 50%	18.91	0.95	13.3	5.3
PHBV75 %: PBAT 25%	21.5	4.7	2.63	0.679

Blending PHBV with PLA can improve the mechanical properties of the resulting blend, and the PHBV 75%: PLA 25% & PHBV 50%: PLA 50% blends have been shown to exhibit balanced tensile properties compared to pure PHBV. The incorporation of PBAT to the blends produced a substantial increase in the elastic modulus values and has a good tensile strength for film applications: providing the best combination of tensile properties and ductility than other blends.

Table 2: Summary of Modulus properties

Sample ID	Modulus (MPa)	
	Average	SD
Neat PHBV	3820	704
Neat PLA	2950	728
Neat PBAT	78.9	4.31
PHBV 50%: PLA 50%	2870	525
PHBV 75%: PLA 25%	3650	365
PHBV 50%: PBAT 50%	1380	208
PHBV75 %: PBAT 25%	2210	300

It is obvious that an increase of PBAT & PLA ratio in the polymer blends affects the mechanical properties. The analysis of the data confirmed a significant increase in elongation at break with the PHBV 50%: PBAT 50% blend and PHBV 50%: PLA 50% blend. These blends exhibited balanced properties compared to neat PHBV. Among the various mixtures, the blend comprising 50% PHBV and 50% PBAT exhibited superior performance in terms of elongation at break, which is a measure of its ability to stretch before breaking. The reason for this is that the PBAT component of the blend has a greater influence, resulting in a notable enhancement in the elongation at break while retaining some of the stiffness offered by PHBV. It's worth noting that the packaging materials for film applications require high flexibility and therefore, in the film processing industry plasticizers are often added. It's crucial to consider the specific application and requirements when determining the optimal blend for elongation at break in films. Conducting further research and experimentation is necessary to select the ideal blend

for a particular application. The elongation at break is influenced by the material used and plays a significant role in producing film packaging. Packaging materials, such as protective plastic packaging, require high elongation at break to prevent failure in challenging circumstances. A higher elongation at break value results in a more ductile and stretchable film packaging material, making it more resistant to stress and strain without breaking; making the films more resilient. However, it is also important to consider other factors such as tensile strength and stiffness to determine the overall performance of film packaging. Therefore, when evaluating the durability of film packaging, it is vital to consider elongation at break along with other mechanical properties. Elongation at break shown in figure 12.

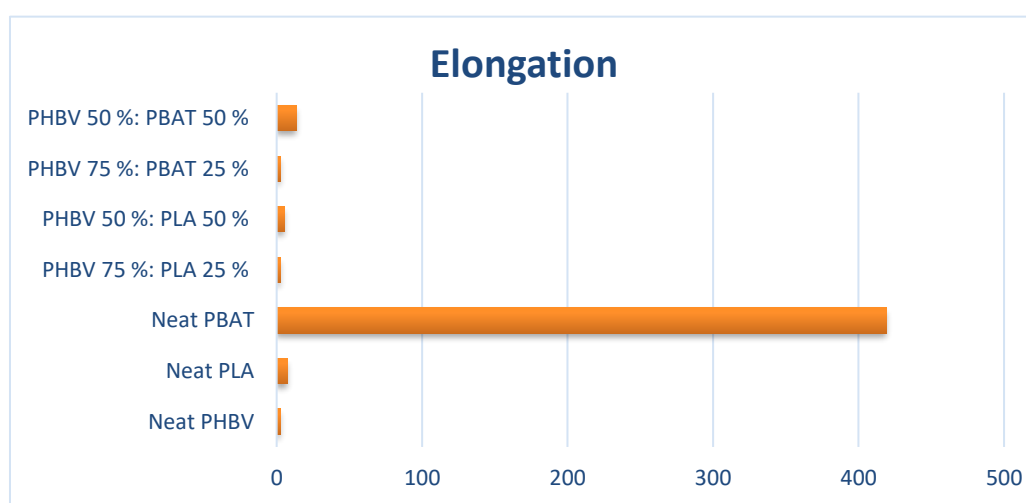


Figure 12: Elongation at break

8.2 DSC

The glass transition temperature (T_g), crystallization temperature (T_c), melting temperature (T_m), obtained from the DSC studies are summarized in Table 3. Figures 13, 14, 15, 16, 17, and 18 show the heating/cooling curves for neat materials and blends.

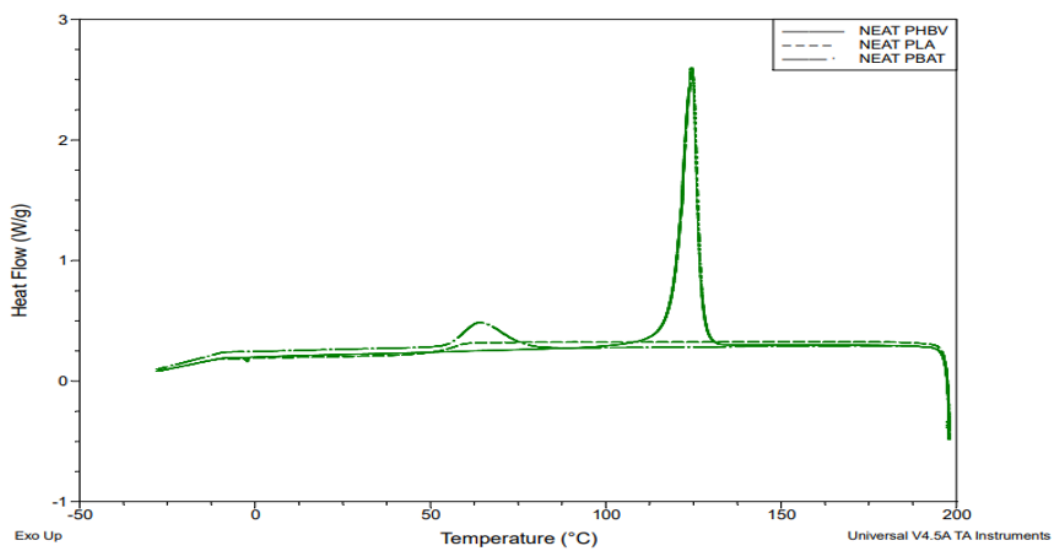


Figure 13: Crystallinity of neat materials

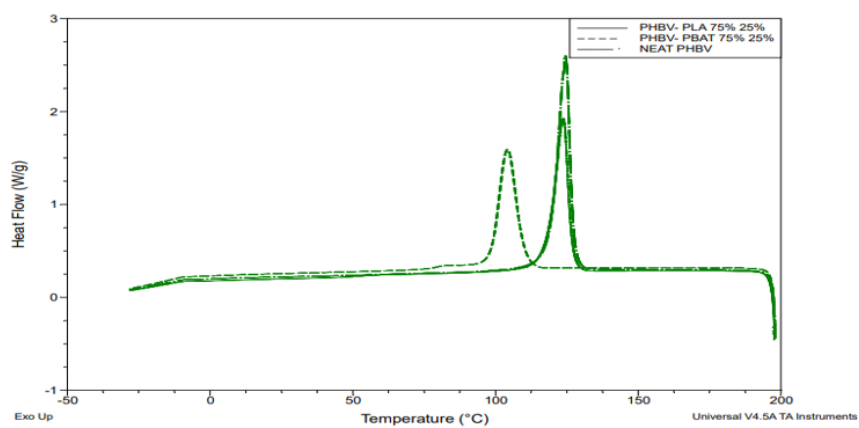


Figure 14: Crystallinity of 75% :25% blends

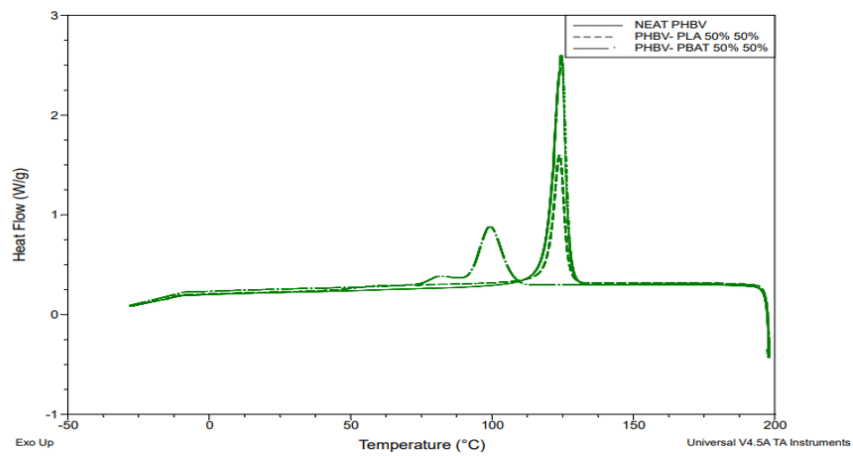


Figure 15 Crystallinity of 50%:50% blends

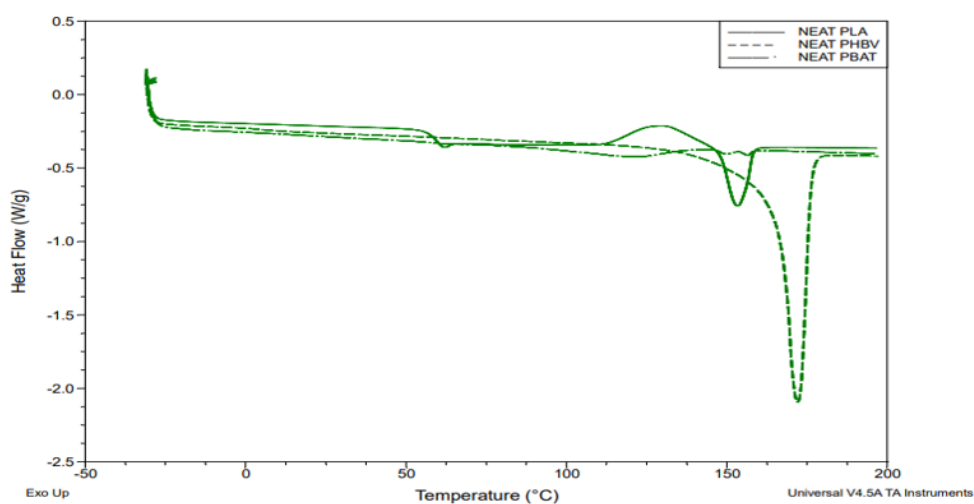


Figure 16: Neat materials enthalpy curves

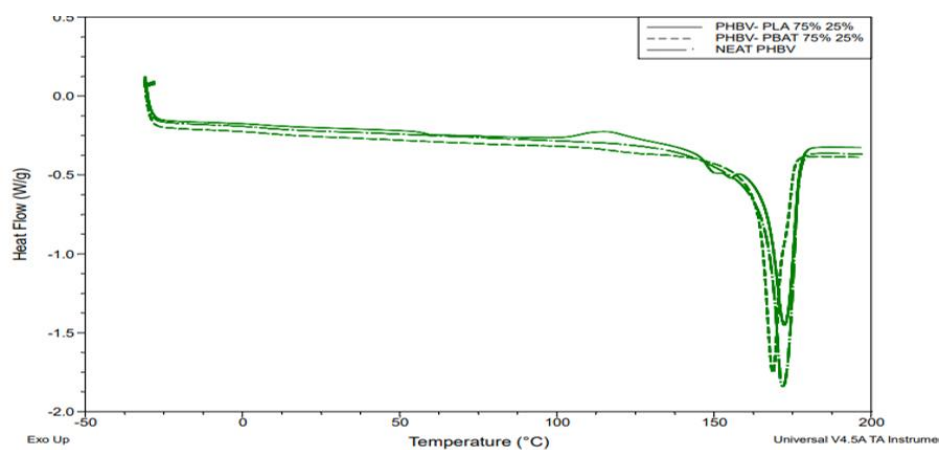


Figure 17: Enthalpy cure for 75%:25% blends

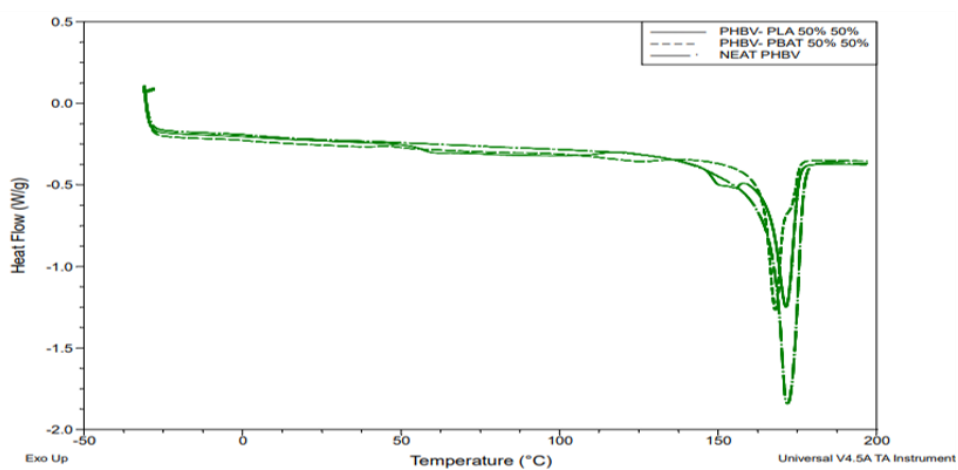


Figure 18: Enthalpy curve for 50%:50% blends

The graph illustrates both exothermic and endothermic thermal events that occurred during a temperature scan from -40°C to 200°C. The endothermic step change (glass transition) occurs first in the scan, followed by an exothermic peak due to “cold” crystallization, which is then followed by the endothermic peak due to melting.

Based on the data presented in Table 3, it was observed that the blends of PHBV: PLA (72%:25%) & (50%:50%) demonstrated a melting point that was higher than the melting point of PLA. This result suggests that blending PHBV and PLA in certain proportions can produce a material with improved thermal stability. Similarly, the blends of PHBV: PBAT (72%:25%) & (50%:50%) showed a melting point that was almost close to the melting point of the raw materials.

Table 3: DSC results of PHBV, PLA, PBAT and their blends

Sample ID	T _g (°C)	T _c (°C)	T _m (°C)	X DSC %
Neat PHBV	X (-5 to 20)	124	172.7	53
Neat PLA	60.4	(100 to 110)	152.7	4
Neat PBAT	(-35 to -30)	64.7 (50 to 110)	156.1	9
PHBV 50%: PLA 50%	X	123.8	171.4	6.5
PHBV 75%: PLA 25%	X	123.7	172.3	4.4
PHBV 50%: PBAT 50%	X	95.6	167	21
PHBV 75 %: PBAT 25%	X	103.4	168	X

X represents the value is not obtained or it is not applicable

Values in brackets obtained from extensive literature study.

Based on the results of the test, the addition of PLA to the mixture had a noticeable impact on the level of crystallinity; the same trend was observed with the addition of PBAT. These findings indicate that PHBV's crystallization properties are significantly influenced by the presence of PBAT and PLA. It is noteworthy that polymer blends can be utilized to manipulate the crystallization, nucleation, and crystal growth rate of polymers. Regarding the blend

PHBV75%/PLA 25% we do not have significant melting peaks in DSC curve, so the crystallinity was not calculated. The incorporation of PBAT into PHBV50% leads to a reduction in a decrease in crystallinity of PHBV. Nonetheless, it is worth mentioning that this mixture still exhibits a substantial degree of crystallinity at 21%, which is the highest compared to the other blends evaluated. This decrease in crystallinity can affect the thermal and mechanical properties of the blend, which should be taken into consideration when using it in various applications and the properties of a polymer blend can be significantly impacted by its degree of crystallinity.

In the case of the PHBV50%: PLA 50% blend, an addition of PLA causes a decrease in crystallinity of PHBV. Additionally, it is important to mention that PLA is poor in crystallization, but it can crystallize better under pressure. In this study, the DSC curve shows the cold crystallinity of PLA.

The level of crystallinity in a material is a critical factor in determining its ability to act as a barrier against gases like oxygen and carbon dioxide. By increasing the degree of crystallinity, we can significantly reduce the permeability of these gases, which is particularly important in preserving food products. Moreover, crystallinity has a substantial influence on other properties of the material, such as density, hardness, transparency, and diffusion. However, predicting the effect of crystallinity on gas barrier properties is complex as it is dependent on the degree and morphology of the crystal structure. Although the impact of crystallinity on the gas barrier properties of PHBV: PBAT & PHBV: PLA extruded films is still under investigation, increasing crystallinity remains the simplest and most affordable way to enhance the gas barrier properties of polymeric materials (McKeen, 2012).

The data indicates that the degree of crystallinity of the polymer PHBV decreased with the addition of PLA and PBAT. The analysis of experimental data suggests that the degree of crystallinity of the polymer PHBV was observed to decrease with the incorporation of PLA and PBAT, indicating that these materials have a significant impact on the physical characteristics of PHBV.

Overall, these findings can provide valuable insights into the development of polymer blends and their physical characteristics, paving the way for the creation of new materials with improved properties. The potential of PHBV blends for producing materials with improved thermal properties. Further investigation of the properties and applications of these blends could lead to the development of new and innovative materials for a range of industrial and commercial applications.

8.3 FTIR

Tests performed in absorption mode in the transmission range of 4000 cm^{-1} to 400 cm^{-1} and the spectra were recorded after 64 scans and at 4 cm^{-1} band resolution. The tests were repeated three times for each batch. The FTIR studies are summarized in Figures 19, 20 and 21. The structures of PHBV, PLA, and PBAT and the blends are shown and the infrared characteristic peaks of PHBV: PBAT and PHBV: PLA were reported.

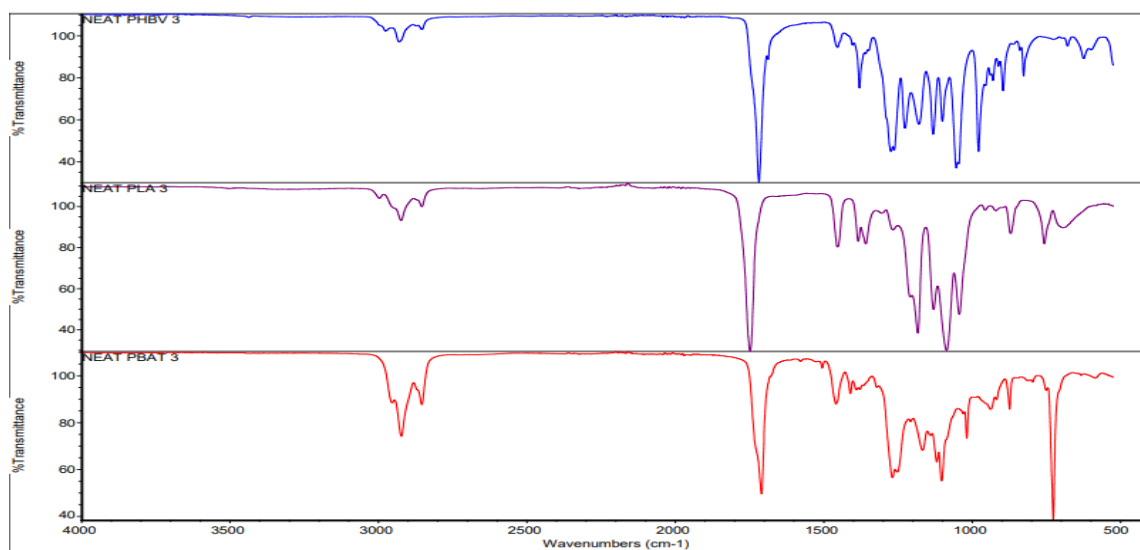


Figure 19: FTIR neat materials

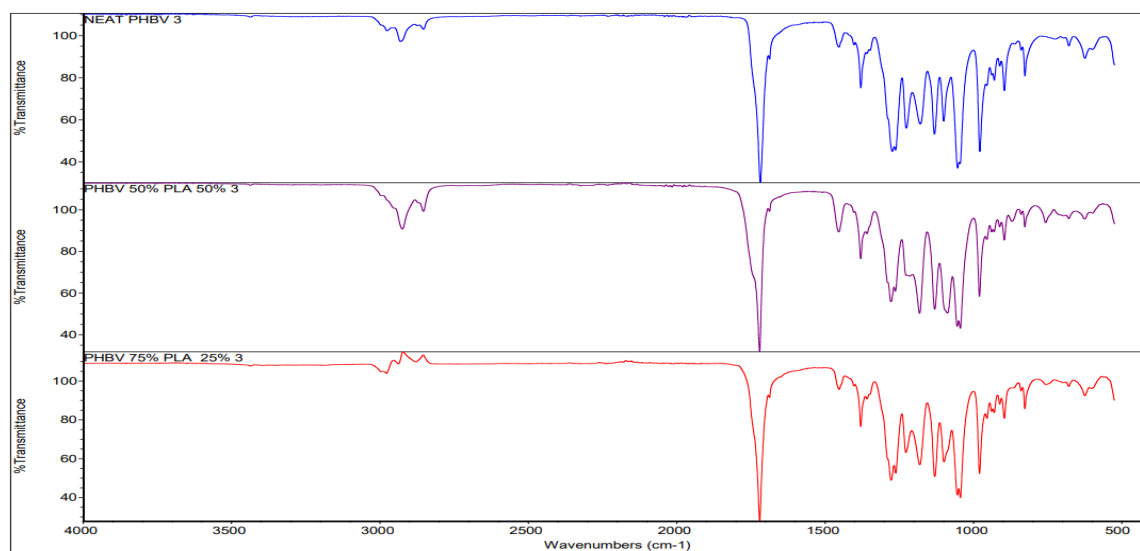


Figure 20: FTIR results, PHBV & PLA blends

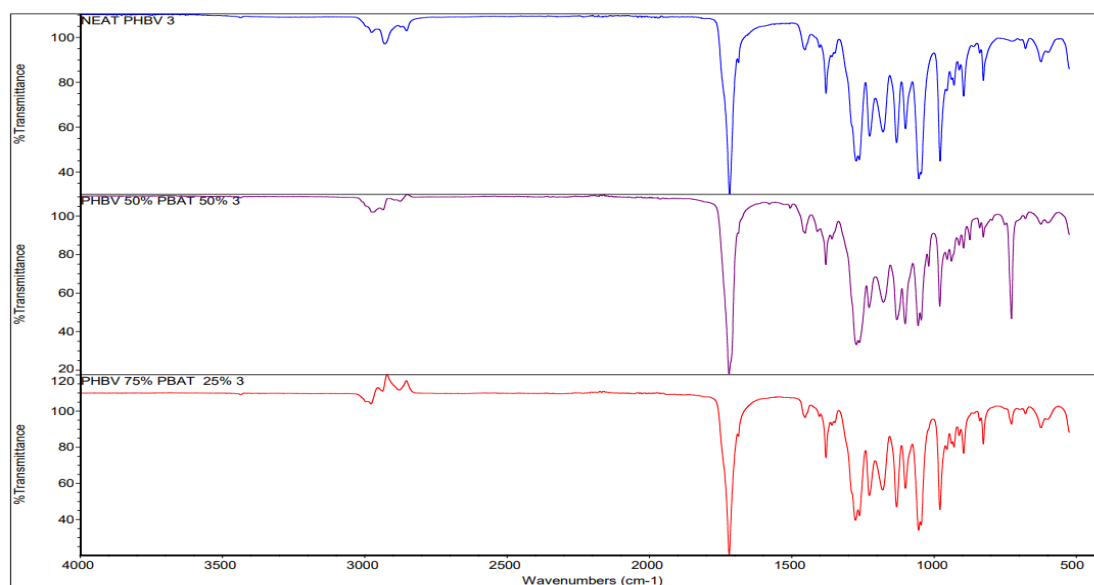


Figure 21: FTIR results, PHBV & PBAT blends

It was observed that the spectra have similar structures and functional groups for neat materials except for neat PBAT, which differed from them with a group of strong C-H stretching around 720 cm^{-1} which refers to the stretching vibration of the CH_2 group. The peak around 2900 cm^{-1} corresponds to medium C-H stretching, observed in neat PHBV, PLA and PBAT. While the peak around $1685\text{--}1700\text{ cm}^{-1}$ corresponding to strong $\text{C}=\text{O}$ stretching and the peak around 970 cm^{-1} corresponds to strong C-C stretching observed in neat PHBV. The peak around 1275 cm^{-1} corresponds to strong C-O stretching observed in both neat PHBV & neat PBAT. The peak around 1100 cm^{-1} corresponds to strong C-O stretching observed in all neat materials (PHBV, PLA and PBAT). The peak around 1706 cm^{-1} corresponds to strong $\text{C}=\text{O}$ stretching observed in both neat PLA & neat PBAT. It is worth noting that the peak around 1200 cm^{-1} was observed only in neat PLA.

The FTIR spectrum of neat PHBV exhibits a strong and sharp absorption band centered at 1734 cm^{-1} , which is attributed to the C-O stretching mode of the crystalline parts in PHBV. Additionally, the absorption bands at 1282 and 1053 cm^{-1} are assigned to the C-O-C stretching modes of the crystalline parts, while the strong band detected near 1188 cm^{-1} is due to the amorphous state of the C-O-C stretching band.

According to the literature, the presence of absorption bands above 2993 cm^{-1} is usually connected with the possibility of hydrogen bond formation. It is also indicated that in the crystal structure, the CH_3 group in one helical structure and the C-O group in the other helical one is

in proximity, and there is a pair of such proximities between the CH₃ and the C–O groups. Therefore, it is considered that a chain of C–H...O hydrogen bond pairs link the two helical structures in the antiparallel orientation (Kennouche et al., 2016, Petit and Puskar, 2018).

For PLA, the absorption band related to C–O stretching vibration is observed at 1754 cm⁻¹. Additionally, a C–H deformation vibration is detected at 1454 and 1375 cm⁻¹, and –C–O–C stretching vibration is noted at 1110 cm⁻¹. Overall, the FTIR spectra of both PHBV and PLA provide valuable information about the molecular structure and properties of these neat polymers. Figure 20 shows FT-IR spectra of the base polymers and various PHBV:PLA blends recorded in the regions 1850–1600 cm⁻¹ and 1000–700 cm⁻¹, respectively.

Figure 20 shows the carbonyl absorption bands of PLA and PHBV, which are of interest due to their characteristic bands in blends of PHBV: PLA. The carbonyl band shifts from 1734 cm⁻¹ for neat PHBV to 1743, 1747 and 1750 cm⁻¹ for 75/25 and 50/50 blend compositions, respectively, indicating changes in the local molecular environment during crystallization. The FT-IR spectrum of PHBV shows two absorption bands at 978 cm⁻¹ and 895 cm⁻¹, assigned to the coupling of C–C backbone stretching with the CH₃ stretching vibration and the crystalline C–O–C vibration bands, respectively. However, the intensity of the absorption bands decreases with an increase in the PLA content in the blends. Conversely, the amorphous band intensity at 869 cm⁻¹ (C–O–C) and 756 cm⁻¹ (C–H) increases with increasing the PLA content. Therefore, the addition of PLA to PHBV alters the helical structure from place to place, leading to a decrease in crystallinity resulting from the formation of a number of amorphous parts. This behavior is illustrated in Figure 20, which shows the decrease in intensity of the whole crystalline absorption bands of PHBV with an increasing ratio of PLA in PHBV: PLA blends, following the order of crystallinity from highest to lowest, i.e., PHBV > PHBV: PLA: 75%:25% > PHBV/PLA: 50%:50% > PHBV: PLA: 75%:25% > PLA (Idris Zembouai, 2013).

The PHBV: PBAT blend system was characterized using FTIR to investigate the relationship between the PHBV and PBAT components. Figure 21 shows the infrared spectra of various PHBV/PBAT mixes with mass fractions of 75%:25% & 50%:50%. The chemical structures of PHBV and PBAT were shown in Figure 21, and the infrared characteristic peaks of PHBV and PBAT were reported. The stretching vibration peak of the C=O in the PHBV molecule was observed at 1724 cm⁻¹, while the stretching vibration peak of the hydroxyl terminal was observed at 3459 cm⁻¹, suggesting the presence of water molecules in the fibers. The antisymmetric stretching vibration and symmetrical stretching vibration of methylene -CH₂ were assigned to the peaks at 2931 and 2861 cm⁻¹, respectively. The stretching vibration peak was found to be at 728 cm⁻¹. The blend system showed the typical absorption peaks of

PHBV and PBAT, as determined by infrared spectrum analysis. Comparison of the infrared spectra of pure PBAT and PHBV: PBAT suggested that no additional characteristic peaks occur in the blend system. There was no variation in the stretching vibration band of any distinct group, indicating that PHBV and PBAT did not form a chemical connection, or that the force between them was extremely low and weak under the experimental conditions. The blending of PHBV with PBAT was a straightforward physical blending process (Jun Xu, December 2022).

8.4 TGA

Neat polymers show single step decomposition in the nitrogen atmosphere. Figures 22, 23 and 24 show change in weight (%) results, while Figures 25, 26 and 27 show derivative weight change results, Neat PHBV and PLA begin to degrade at around 300 °C and at around 380 °C respectively, while the PHBV 75%:PLA 25% blend around 320 °C and PHB 50/ PLA 50% blend degradation begin around 375 °C. Neat PBAT starts to degrade around 430 °C, while the PHBV 75% / PLA 25% blend begins to degrade around 315 to 410 °C and PHBV50%: PBAT 50% start to degrade at 350 to 430 °C, respectively. The difference in thermal stability between the neat polymers and blends results in two distinct stages of degradation, the first being when PHBV degrades followed by the more stable PBAT component. The PHBV portion of blends shows slightly improved thermal stability because of the PBAT blending, with an approximately 20 °C improvement in both the 75/25 and 50/50 blend. The influence of PBAT increases at higher weight percentages, which explains the delayed onset of degradation in PBAT blends. The insertion of PBAT into the polymer blends retards decomposition, leading to a slightly higher thermal stability of the blends compared to the neat polymers.

The addition of PBAT (poly(butylene-adipate-co-terephthalate)) to other polymers can enhance thermal stability due to its crystallinity and inherent thermal stability. Increasing the amount of PBAT in a blend can also improve phase dispersion and ductility, which can contribute to better thermal stability. However, the effects of PBAT may vary depending on the specific blend and processing conditions (Jian et al., 2020).

There are no significant changes in the onset degradation temperature of PHBV: PLA. These results are in line with the requirements and properties of packaging materials that should have high thermal stability.

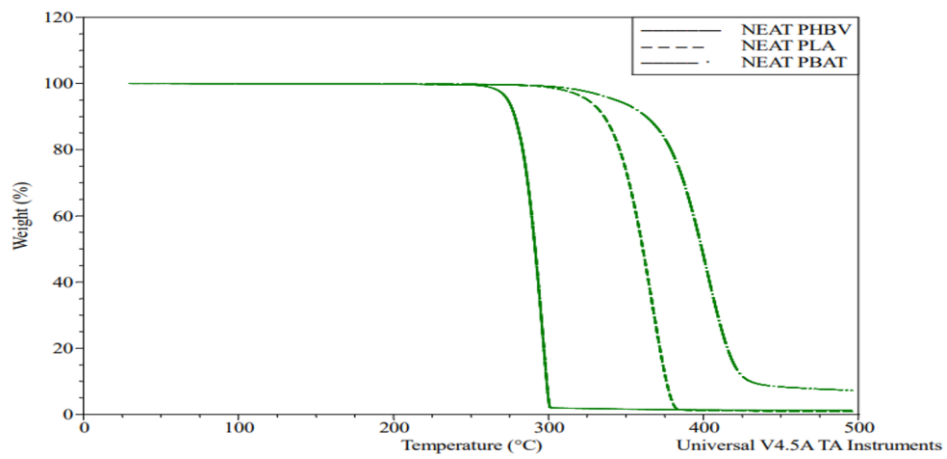


Figure 22: TGA weight results, neat materials

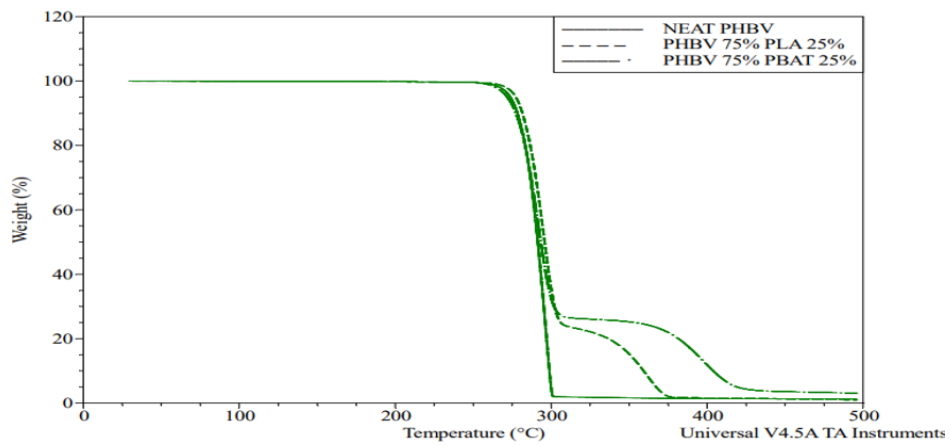


Figure 23: TGA weight results 75%:25% blends

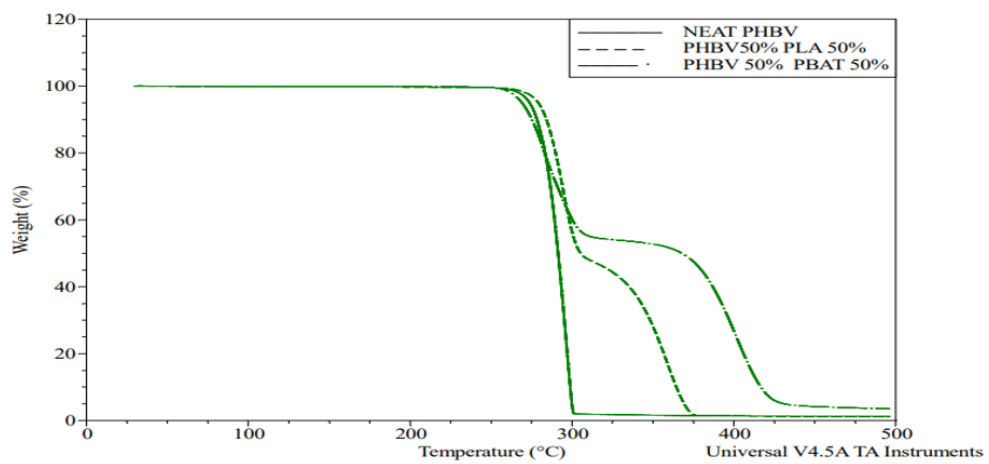


Figure 24: TGA weight results 50%:50% blends

The derivative of weight loss curves in figures 25,26 and 27 represent the rate of change of degradation at each degree of temperature increase. The onset of degradation for the PHBV blends shifts slightly higher with increasing PBAT content. Samples with 50% PBAT content show an increased thermal stability compared to neat PHBV.

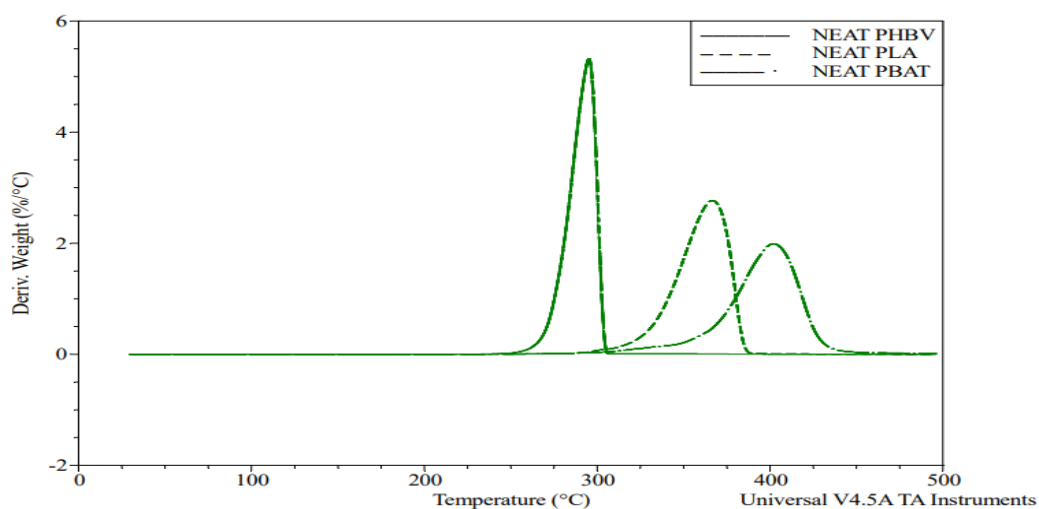


Figure 25:TGA Derive weight, neat materials.

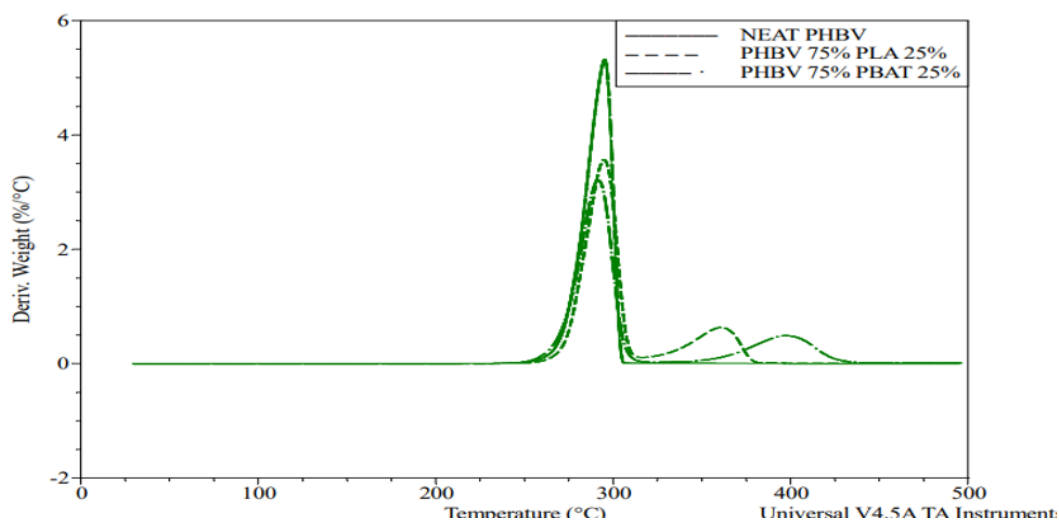


Figure 26:TGA Derive weight 75%:25% blends.

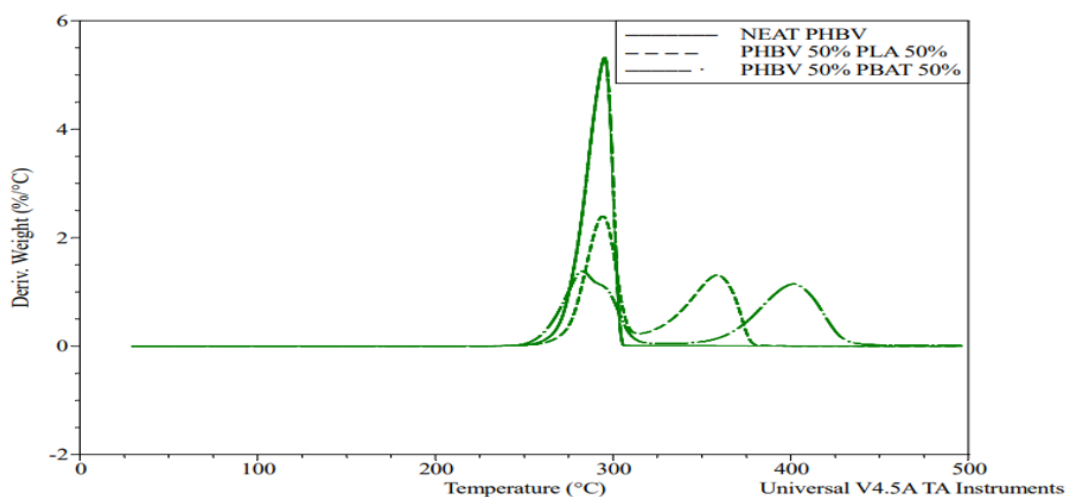


Figure 27: TGA Deriv. weight 50%:50% blends.

8.5 Oxygen and water vapor barrier (WVTR)

When it comes to selecting the right packaging materials, it's crucial to consider their capacity to prevent the permeation of oxygen and water vapor. To ensure this, we carried out a series of tests on biodegradable composites, specifically measuring their transmission rates of pure oxygen and saturated water vapor under carefully controlled temperature and pressure conditions.

By analyzing these results, we can make informed decisions on which packaging materials will offer the most effective protection for our product. The properties of different biopolymers and the transmission rate measures the amount of permeant passing through a unit area per unit time at certain temperature and pressure conditions are listed in Table 4. The test result investigations indicated that PHBV50%: PBAT50% blends offering a good barrier property against water vapor and oxygen and it's undoubtedly promising.

Table 4: WVTR results of PHBV, PLA, PBAT and their blends.

Material	Thickness [um]	Std.dev Thickness	WVTR [g/m ² day]	Std.dev WVTR
Neat PHBV	111.2	8.2	3.3	0.3
Neat PLA	152.0	5.3	16.7	2.6
Neat PBAT	217.6	32.3	21.5	4.0
PHBV 75%: PLA 25%	126.1	7.1	5.1	1.3
PHBV 50%: PLA 50%	139.6	8.8	5.6	1.2
PHBV 75%: PBAT 25%	130.0	8.5	5.8	0.6
PHBV 50%: PBAT 50%	130.8	4.4	10.4	1.1

9. Conclusion

This set of results demonstrates the interest in preparing PHBV 50%: PBAT 50% blends and the possibility to control their structure and thermal properties. Moreover, PBAT involves more significant changes in mechanical, thermal and barrier properties than PLA. The ductility has improved significantly due to the addition of PBAT.

Both the low-toughness PHBV and a semi-crystalline of the PBAT work in conjunction to improve the mechanical performance of the blends such as the good tensile strength and Young's modulus. This exchange is expected and must be taken into consideration by scientists and engineers when designing new blends for specific applications such as packaging.

It should be noted that:

- Significant changes in mechanical performance of formulation PHBV 50%: PBAT 50%
- Based on the DSC data, it was observed that the addition of PLA and PBAT to the mixture had a noticeable impact on the level of crystallinity. The crystallinity of all blends decreased in comparison to the neat PHBV and other raw materials. It is worth noting that the blend of PHBV 50%: PBAT 50% exhibited the highest crystallization rate when compared to the other blends tested.
- TGA investigations indicated that PHBV 50%: PBAT50% is thermally stable than other blends.

- FTIR investigations indicated that there is no difference in vibration absorption peaks between the blends and the neat material.
- WVTR investigations indicated that PHBV 50%: PBAT50% blends offering a good barrier property against water vapor and oxygen.

Ultimately, the results suggest that the combination of PHBV50%: PBAT 50% shows apparent promising properties compared to the other blends. PBAT, a flexible copolymer, is ideal for combination with other polymers that have good elastic modulus and strength but are very brittle like PHBV. In this study, the properties of PHBV were improved by reducing the high brittleness. Therefore, it is worthy to say that physical modification is one of the most common methods to overcome the brittleness of PHBV and improve its thermal properties, and barrier properties by blending it with other materials and plasticizers if required. Besides that, our results also indicate that PHBV50%: PBAT 50% films offer a variety of benefits, including superior ductility, toughness, and a strong gas barrier property. The potential of these films to degrade makes them a viable contender for replacing classical nondegradable packing films.

10. Perspective for the future

Although the study has found positive results, there is still work to be done. By using a combination of natural and synthetic polymers, various bioplastics can be created based on different PHA blends, which can potentially replace traditional plastic. By employing various blending techniques, the undesirable properties of PHAs, such as their crystallinity and brittleness, can be reduced. However, due to the high cost of PHA, blending is the most cost-effective approach to bridge the financial gap and speed up commercialization. In the upcoming years, PHAs and their blends could greatly benefit a range of applications, including tissue engineering, 3D printing, bioremediation, drug delivery systems, and food packaging. The author would like to point out that due to time constraints, the step that has not been dealt with in this work is the process of adding a plasticizer, additive, and antimicrobial agents, and studying their effects.

Further research and experimentation may be necessary to fully understand and optimize the properties of these blends for food packaging applications. With continuous efforts to obtain a large-scale supply of PHA, the development of PHA as a new biodegradable material will open doors for a new future. Overall, future research on food packaging should aim to develop sustainable packaging solutions that minimize environmental impact while maintaining

food quality and safety. This could involve exploring new materials, technologies, and design approaches.

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