

Increased Elongation at Breaking Point with Improved Mechanical Characteristics in PLA

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Abstract

The main goal of this research was to increase the strength of Polylactic acid (PLA), an entirely biodegradable thermoplastic polyester, and an increase in elongation at the breaking point compared to neat PLA. To this end, S1, S2, and S3 were melt blended with various percentages of Zeolite, Glycerol, White vinegar, green camphor, Eucalyptus, and Carom seed oils. Here, the addition of glycerol, eucalyptus, and carom seed oils demonstrated an average improvement in impact and tensile strength of 13.44% and 14.55% respectively. Zeolite and glycerol work together as binding agents to improve stress transfer in the matrix, which increases tensile and flexural modulus as well as toughness elongation (>10%). The addition of the aforementioned materials led to an increase in the glass transition temperature and melting temperature, according to further DSC investigation. The thermal stability increased gradually, according to TGA data.

Keywords

Polylactic Acid, Biodegradable Thermoplastic Polyester, Elongation, Zeolite, Glycerol, Toughness Elongation, Thermal Stability

1. Introduction

The majority of composite materials utilized during the past few decades have been non-biodegradable petrochemical compounds including polyethylene, polypropylene, and polyethylene terephthalate (PET). Plastic waste in landfills must be stopped immediately given the rising concern about environmental contamination. The creation of degradable plastics has also received attention due to the growing global environmental issues like greenhouse gas emissions and depleting fossil fuel resources [1]. Using biodegradable polymers can help

manage packaging waste. Since they are environmentally friendly, compostable, biodegradable, and made from sustainable and renewable resources, biodegradable plastics are a hot topic in green chemistry. Additionally, they lessen our reliance on finite fossil fuels and the production of dangerous compounds [2]. Aliphatic polyesters and proteins, including poly (lactic acid), poly (3-hydroxybutyrate), poly (caprolactone), and starch, are the most often utilized biodegradable polymers [3]. PLA is one of the thermoplastic materials currently being explored that is both promising and appealing. Corn, potatoes, sugar beets, and sugar cane are examples of naturally existing biomass that can be fermented with glucose to produce PLA [4] [5]. Commercially, PLAs can be produced by either ring-opening polymerization of the cyclic lactide dimer (lactide monomer) or condensation polymerization of lactic acid (2-hydroxy propionic acid) [6]. PLA, a linear aliphatic polyester, is regarded as one of the most innovative alternatives to traditional petroleum-based polymers, because it has similar mechanical properties to PET in terms of density, glass transition temperature (T_g), tensile strength, and young's modulus [7]. Furthermore, PLA has high potential due to its superior properties, which include good mechanical properties (particularly strength and modulus), ease of processing, excellent degradability, and transparency [3]. The main disadvantages of PLA are its high brittleness, low toughness, and low tensile elongation [8].

The majority of materials used today in the food packaging sector for throwaway applications are synthetic plastic films. However, the vast majority of plastics are not biodegradable in nature, and the food packaging sector has been inspired to create new biodegradable packaging materials by expanding synthetic plastic waste [9]. Since the creation of biobased antimicrobial packaging materials could lessen environmental consequences while proving protection of products against chemical, physical, and microbiological effects, there has been a great deal of attention in the field of food packaging [10] [11]. Because of its potential commercial use, biopolymer poly (lactic acid) is a viable alternative to synthetic plastic. Corn, sugar beet, and potato starch are just examples of renewable materials that can be used to create PLA, a flexible and biodegradable thermoplastic polymer [12]. Furthermore, PLA has been demonstrated to be "Generally Recognized as Safe" (GRAS), making it safe for use in food packaging applications [13]. However, its toughness, deformation at the break, and thermal characteristics are poor compared to traditional petroleum-based materials. This would restrict its use in food packaging. For PLA to compete with other commodity plastics films, a lot of work has been done to enhance its qualities. Biodegradable polymer films can integrate active substances like essential oils to enhance their mechanical and antibacterial capabilities, among other functional qualities [14]. The US Food and Drug Administration and the present European legislation for materials intended to encounter foodstuffs both classify plant essential oils to PLA films. Active antimicrobial packaging may protect the PLA from chemical, physical, and microbial damage [10].

Zeolites are hydrated aluminum-silicate crystals with micropores, there are about 200 synthetic and 40 naturally occurring grades of zeolites [15]. Zeolites are aluminum-silicate-based frameworks with a three-dimensional $[\text{AlO}_4]_5$ and $[\text{SiO}_4]_4$ tetrahedral structure that are related to one another by sharing all their oxygen atoms. Zeolites are frequently utilized in particle form as catalysts, detergent builders, ion exchangers, and gas separation media because of their exceptional thermal and chemical resilience. Other possibilities for this adaptable, affordable substance include personal hygiene products that eliminate odors and have medical uses. All these applications benefit from the zeolite's uniform microporosity (and even nanoporosity, which allows applications by the separation or sieving of molecules according to their size with an accuracy of a fraction of a nanometer), which ranges from 0.3 to 1.3 nm. It is interesting to note that new uses for zeolite may involve incorporating them into thermoplastic polymers to lessen odor and VOC emissions [16] [17], as well as serving as carriers for silver particles to create functional materials with potential antibacterial activity [18] [19] [20].

Yuzay *et al.* [21] also reported that melt-compounding preparation of PLA (94% Lactide)-synthetic zeolite (4A, Si/Al = 1, pore size of 38 - 40 nm) composites and the effects of 4A synthetic zeolites on PLA physical-mechanical properties. PLA composites containing up to 5% zeolite 4A were prepared using a micro extruder (melt compounding temperature at 185°C), and test specimens were prepared using mini-injection molding for physical and mechanical characterization. The TEM and SEM images of the composites showed no void formation around zeolite particles or cavities in the PLA matrix, indicating that there is good interfacial adhesion between the zeolite and this polyester, which is supported by mechanical testing. Additionally, utilizing the extrusion/injection molding procedures, these authors reported the creation of PLA composites comprising of 5 wt-% natural (chabazite, CHA, Si/Al 2.4-3.4) and synthetic (type 4A, framework type LTA) zeolites [21]. The glass transition and melting temperatures and chabazite zeolites improved PLA crystallite nucleation and raised the % crystallinity, according to the TGA data, PLA-zeolite 4A composites thermally disintegrated more quickly than PLA and PLA-chabazite composites at temperatures above 300°C.

A bio-based monomer that combines the aforementioned requirements is glycerol. The main byproduct of biodiesel synthesis is glycerol (1,2,3-propanetriol), whose annual production capacity has increased by nearly 2 million tonnes during the past ten years. As a result, new uses for glycerol are sought in order to further the biorefinery idea in the biodiesel industry [22] [23]. Glycerol and succinic acid can be used to create biodegradable polyesters in bulk polycondensations in the absence of catalysts or solvents. These polyesters can be referred to as "green" polyesters since they follow the principles of green chemistry and are produced utilizing renewable resources under environmentally friendly reaction conditions with no harmful byproducts [24] [25]. Two instances of PLA that has

been made tougher by melting polyesters containing glycerol are documented in older literature [26] [27]. Gu and colleagues made the first known attempt to create PLA/glycerol polyester strong material. Using glycerol and sebacic acid as the components, the authors created a polyester in this ground-breaking work, which they then utilized to melt mix with PLA. The elongation at break of PLA rose from 7 to 155% to 143% with addition of 15 and 30 wt-% glycerol polyester, respectively. Recently, Coativy and colleagues reported a second instance of the use of glycerol-based polyesters for themodifications of PLA [28]. Glycerol (5% - 8%) was used as the initial monomer in this work to enhance PLA properties, in this instance, the systems elongation break rose from 3.9% for pure PLA to 141.02% in the blend of 8% glycerol PLA. So far, no research has been done on the behavior of PLA/glycerol polyester blend system. Additionally, there is no research that links the mechanical performance of PLA/glycerol polyester blends with glycerol polyester's synthesis condition.

Adding a porogen to the polymer solution and then leaching it out using a solvent that doesn't dissolve the polymer is onemethod of creating fully porous constructions. The porogen must allow for the creation of homogeneous structures and be nontoxic and soluble in both polar and nonpolar solvents. Several techniques, including the introduction of micronized crystalline agents into polymer systems [29] [30], the lyophilization of frozen solutions [31], and thermally induced phase separation [32], can be used to create porous structures. However, no sufficiently robust porous structures with consistent mechanical, physical, and structural characteristics have yet to be created. Camphor, a volatile crystalline material that is easily soluble in a variety of organic solvents, including both alcohols and organic halogen solvents (used to create polyester solutions), is one of the compounds that satisfies these conditions (which do not dissolve polyesters and can, thus, be used to remove camphor from the mixes). Camphor is not poisonous when taken moderately and can be beneficial to health [33]. In this study, porous structures made of degradable polymers were created utilizing camphor as porogen. Their characteristics were examined, and they were tested as prospective cell scaffolds.

2. Experiments

2.1. Materials

Polylactic acid granules, NatureWorks LLC Ingeo™ Biopolymer commercial grade 4043D were purchased from Reprapworld.de (Germany) with 1.24 g/cc as density. Zeolite powder (0.4 nm) with 44% porosity having thermal stability of more than 450°C was purchased from Cellavita^R GmbH & Co.KG, Haustein Germany. Clove oil and Eucalyptus oil were purchased from Naissance GmbH and Casida GmbH Germany respectively. Glycerol with 99.7% concentration having a calorific value of 1804.9 KJ/431Kcal was purchased from FloraCura GmbH, Garmisch-partenkirchen Germany. White vinegar, Carom seed oil, and Green Camphor were purchased from India.

2.2. Design of Experiments

Materials	S1 PLA (500 grams)	S2 PLA (500 grams)	S3 PLA (500 grams)
Zeolite	5%	10%	15%
Glycerol	5%	6%	8%
White Vinegar	1.05%	1.20%	1.60%
Eucalyptus oil	0.5%	0.5%	0.5%
Carom seed oil	1.5%	1.5%	1.5%
Green camphor	1%	2%	3%
Clove oil	1.5%	1.5%	1.5%

2.3. Processing

To obtain a uniformly mixed PLA substance that was irregular in shape and size, the compositions of S1, S2, and S3 that were depicted in 2.2 Material composition were melt blended using a Thermoscientific twin screw rotating mixer, also known as a Kneader, at 165°C and rotor speed of 30 rpm. With the aid of a granulator, these compounded PLA lumps were once more transformed into 3 - 5 mm granules. After that, standard samples were obtained in an injection molding machine which were characterized for Mechanical and Thermal properties.

2.4. Measurements

Three Portions of 500 grams each were made out of a total of 1500 grams of PLA. Zeolite and Green camphor were added in accordance with respective percentages using the weighing machine. They are directly added to the PLA with their appropriate ration measures since they are solids.

The ratio measurements for liquids, such as glycerol, vinegar, etc., were determined by estimating their mass using the density formula.

Different ratios were calculated in the following shown way, and the corresponding masses were added to the PLA using a weighing machine. Similarly, the same approach was applied to the remaining liquids.

$$\text{Density}(\rho) = \frac{\text{mass}(\text{grams})}{\text{volume}(\text{cm}^3)}$$

For Example,

Density of Glycerol = 1.26 gram/cm³,

Volume = 5%.

$$\text{Mass} = \text{Volume} \times \text{Density}$$

Mass = 5 × 1.26,

Mass = 6.30 grams,

Note: An error of (±) 0.5 gram has been followed.

2.5. Tensile Test

Based on the DIN EIN ESO 527 test standard, a tensile test was performed in the ASTM D638 utilizing the Zwick Universal Testing equipment. For each compo-

sition, five standard dumbbell-shaped specimens were created. The test was run with the following parameters: 0.1 N preload, 1% mm/min tensile modulus, 115.00 mm grip-to-grip separation at the starting position, 10 kN maximum force, and 5 mm/min speed. Using test Xpert III testing software tensile strength, tensile modulus, and elongation at break were measured. The resultant value was calculated as the average of five results.

2.6. Flexural Test

The flexural test was carried out using the Zwick Universal testing machine which is based on the DIN EIN ESO 178 3-point test standard, a flexural test was performed in the ASTM D790. For each composition, five standard specimens with a length of 80 mm to a width of 10 mm and a thickness of 4mm were created. The test was run with the following parameters: 0.1 MPa preload, 2 mm/min flexure modulus, and 10 mm/min test speed. Using test Xpert III testing software flexural strength, flexural modulus, and elongation at break were measured. The average of five outcomes was used to calculate the outcome value.

2.7. Izod Impact Test

The Charpy impact test was conducted using Rayran advanced universal pendulum and an ASTM D6110-compliant test standard from RAY-Ran test equipment Ltd. Warwickshire, UK. This device has the following features: Hammer weight of 0.95 kg, impact energy of 4 joules and impact velocity of 2.9 m/s. Five specimens with dimensions of 80 mm in length, 10 mm in width, and 4mm in thickness were tested for each composition. In order to determine the impact strength (Kj/m^2), the energy obtained was divided by the thickness of the specimen. The resultant strength was calculated as an average of five results.

2.8. Thermogravimetric Analysis (TGA)

The thermogravimetric Analyzer (TGA4000) from Perkin Elmer was used to investigate the sample's thermal stability. The samples were heated from 30°C to 600°C at a rate of 10°C/min using a weight of approximately 7.33 mg. The analysis was done in a nitrogen atmosphere with a 20 mL/min nitrogen flow rate. Sample weight loss as a function of temperature was measured and plotted.

2.9. Differential Scanning Calorimetry (DSC)

The Perkin Elmer DSC 7 from Perkin Elmer LAS GmbH, Rodgau, Germany, which is based on the DIN EN ISO 11375-4 test standard, was used to conduct glass transition (T_g), melting (T_m), and crystallization (T_c) behavior tests on the blends. With nitrogen gas flowing rate at a rate of 50 mL/min, the scan was performed at a temperature rate of 20°C/min from 25°C to 210°C. The method makes use of differential heat flow and temperature, which are typically connected to material transition. The average of five outcomes was used to calculate the outcome value.

3. Results and Discussion

3.1. Mechanical Properties

Comparing neat PLA to the increased tensile properties. **Figure 1** shows the pictorial representation of samples S1, S2, and S3 PLA which have undergone the tensile test, and similarly bending tests were performed on S1, S2, and S3 PLA representing **Figure 2**. The tensile modulus of S1 and S2 has increased by 5.7% and 33.8% respectively and S3 has decreased by 2.85%. The tensile elongation at break has significantly increased in S1, S2, and S3 by 35.89%, 82.05%, and 141.02% respectively. **Figure 3** shows the graph which is plotted between tensile modulus and elongation at break in %. The tensile strength of S2 and S3 has increased by 5.7% and 23.46% respectively as shown in **Figure 4**. Polylactic acid has a hydroxyl group (OH) at one end and a carboxyl group (O = H) at the other, whereas glycerol has hydroxyl groups at both ends. When combined in a plasticizer, the hydroxyl and carboxyl groups are polar, which improved the tensile properties of PLA. Despite acting as binding agents, zeolite and glycerol increased the matrix's stress transfer, increasing the flexural modulus and toughness elongation. In comparison to neat PLA, the flexural modulus of S1, S2, and

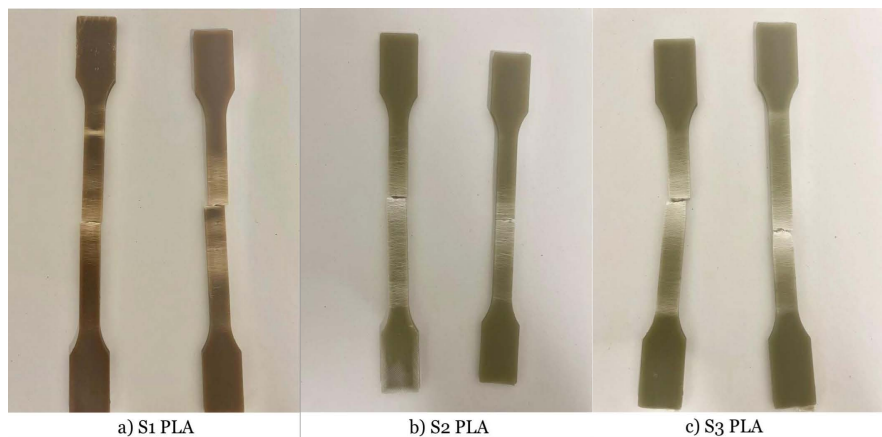


Figure 1. Tensile samples following the test.

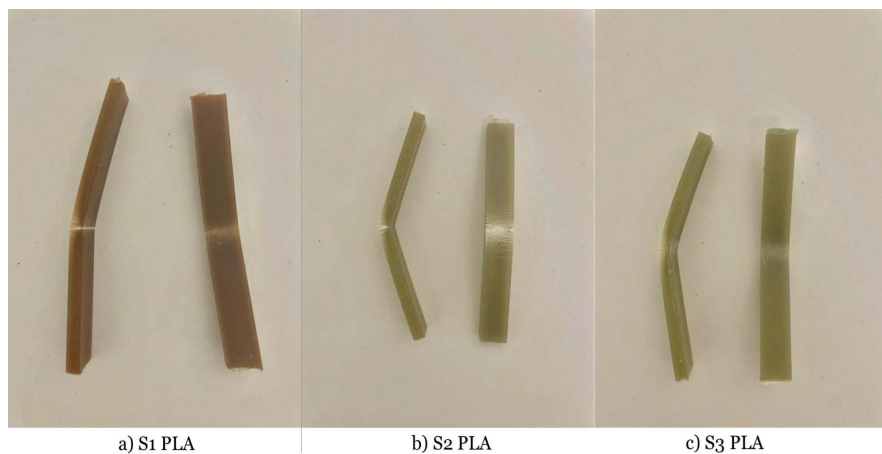


Figure 2. Flexural Samples following the test.

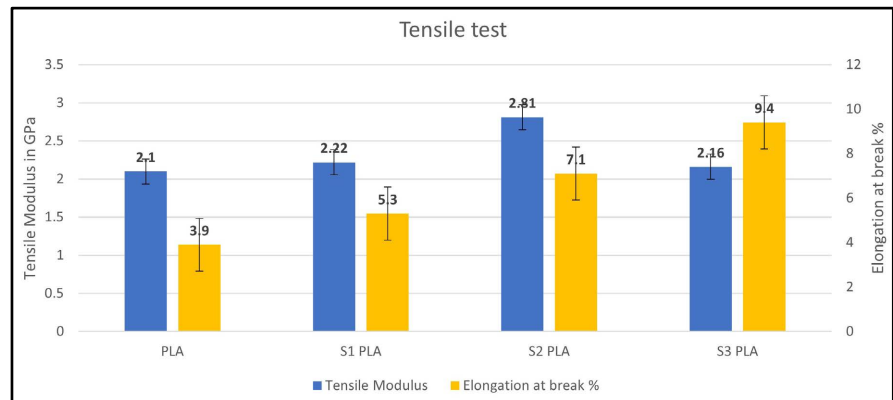


Figure 3. Tensile modulus vs Elongation at break.

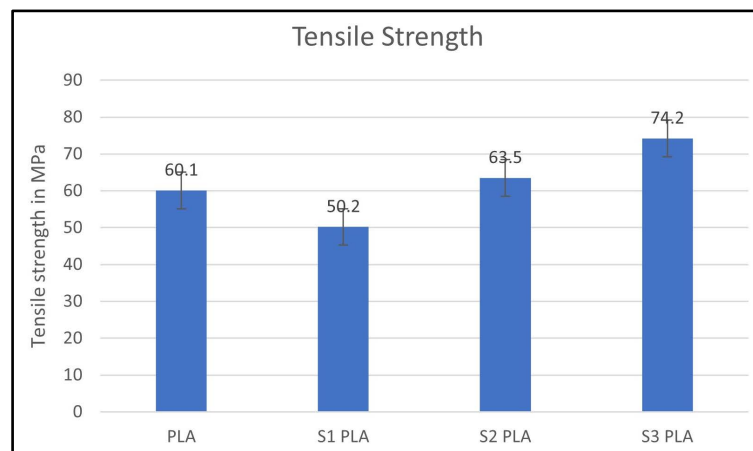


Figure 4. Tensile strength in MPa.

S3 have raised by 13.90%, 24.66%, and 4.93% respectively. In S1, S2, and S3 the flexural strain at the elongated breaking point has increased by 34.83%, 51.68% and, 46.06% respectively as shown in **Figure 5**.

The interfacial adhesion between the chemical bonds was created by the addition of glycerol and oils with various percentages. This increased toughness while concurrently lowering the plasticizer content in neat PLA resulting in an increase in impact energy.

Figure 1 and **Figure 2** illustrate the samples that have already undergone testing; here, variations in materials percentages reveal a distinct physical structural shape, whilst deformation and color changes indicate a range of material percentages from low to high.

Figure 2 depicts the varied zeolite and glycerol concentrations clearly demonstrates an improvement in flexibility inside S1, S2, and S3 PLAs.

The visual representations of Charpy impact tested samples were shown in **Figure 6** to compare the impact energies of S1, S2, and S3 PLA to neat PLA. When glycerol and oils were added to the PLA matrix, the impact energy was seen to rise, resulting in S1, S2 and S3 PLA having impact energies of 20.82 KJ/m², 20.95 KJ/m² and 21.06 KJ/m² respectively, whereas neat PLA has an

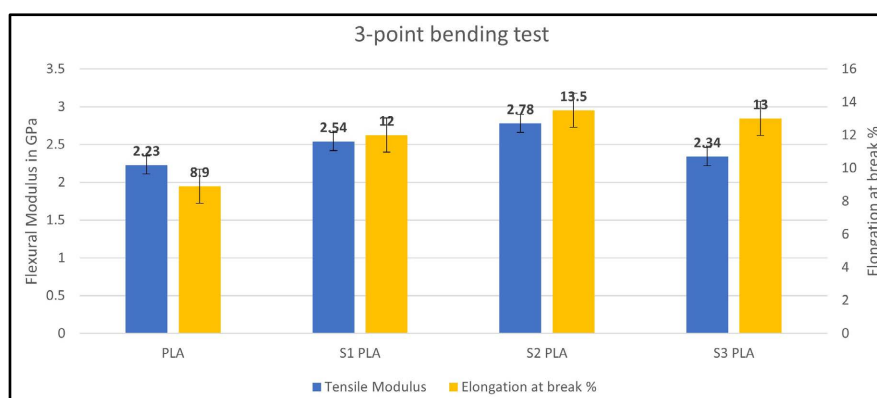


Figure 5. Flexural modulus vs Elongation at break.

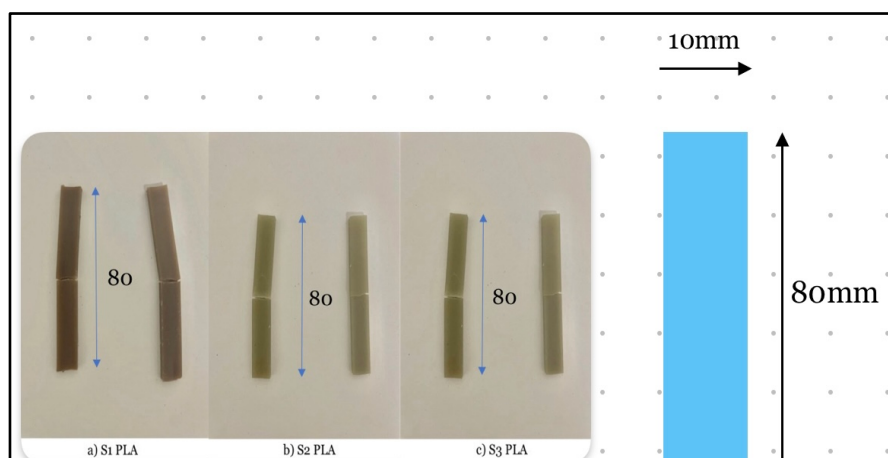


Figure 6. Charpy impact samples following the test.

energy of 18.46 KJ/m² as shown in **Figure 7**. The energy needed to cause fracture has increased as a result of the chemical bonds interfacial adhesion.

3.2. Thermal Properties

3.2.1. Thermogravimetric Analysis

TGA was used to investigate the thermal degradation behavior of plasticized PLA and through weight loss steps, provides information on the structure of inserted molecules. The characteristic thermal parameters chosen were onset temperature, which is initial weight loss temperature and maximum degradation rate temperature obtained from the peak of DTG thermograms. The neat PLA onset temperature was shown around 347.62°C, while for S1, S2 and S3 were 326.40°C, 343.34°C and 345.57°C. As of right now, 5% - 15% of zeolite and 1% - 3% of green camphor were leading the PLA to thermally stable up to 345.57°C which is 0.58% less than neat PLA. Zeolite and green camphor are both thermally stable in addition to having good porosity when combined with glycerol and white vinegar and when excess percentage is added, it will increase thermal stability. **Figure 8** shows the graphical representation of onset temperatures of S1, S2 and S3 PLA reference with neat PLA.

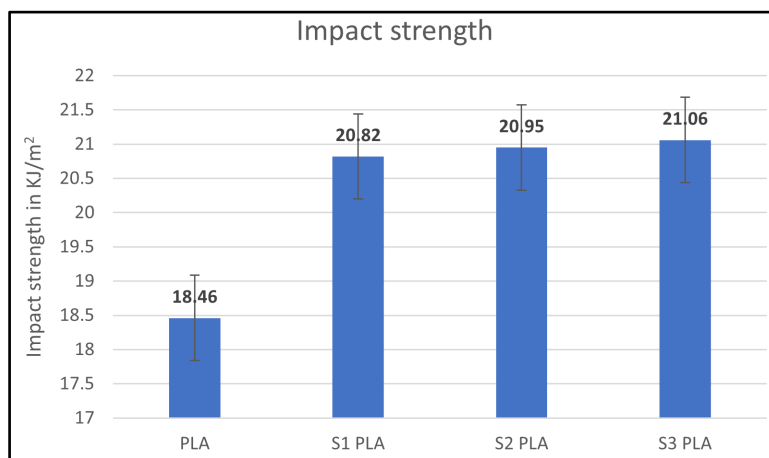


Figure 7. Impact Strength in KJ/m².

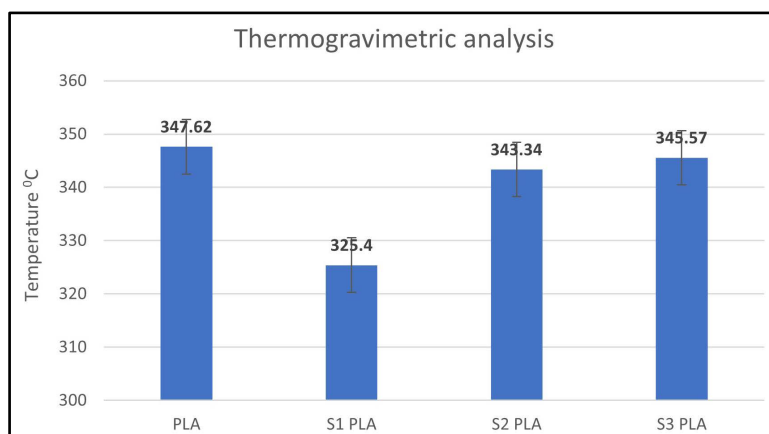


Figure 8. Thermal onset temperatures in °C.

3.2.2. Differential Scanning Calorimetry

The DSC is a thermoanalytical technique in which the difference in the amount of heat required to raise the temperature of a sample and reference is measured as a function of temperature. Throughout the experiment, both the sample and the reference are kept at approximately the same temperature. The DSC curves exhibit three thermal transitions: glass transition (T_g), melting (T_m), and crystallization (T_c). Because of the decrease in plasticity in the PLA matrix, the T_g , T_m , and T_c values of S1, S2, and S3 have been increased when compared to neat PLA as shown in **Figure 9**. The addition of glycerol, zeolite, and green camphor reduced the PLA chain mobility to some extent, resulting in an increase in T_g , T_m , and T_c .

The new T_g values of S1, S2, and S3 are 57.81°C, 54.26°C and 55.46°C respectively, representing a 13.53%, 6.5%, and 8.9% increase over neat PLA, which is around 50.92°C. The new T_m values of S1, S2, and S3 are 147.79°C, 150.68°C and 149.49°C respectively, which is an increase of 5.63%, 7.7%, and 6.85% increased over neat PLA, which is around 139.9°C. This is due to the strong intermolecular forces in the PLA matrix. Glycerol and white vinegar, which contain double

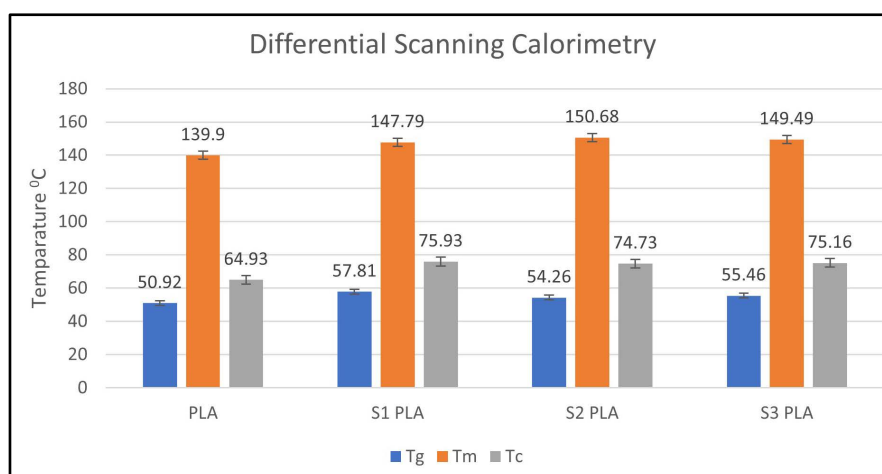


Figure 9. Comparison of T_g , T_m , and T_c with PLA with different compositions of PLA.

bonds, and green camphor which is an aromatic and volatile compound limited the flexibility of the polymer chain resulting in an increase in T_m .

The updated T_c values of S1, S2, and S3 PLA are 75.93°C, 74.73°C and 75.16°C respectively representing a 16.94%, 15.09% and 15.75% increase over neat PLA, which is around 64.93°C. This is due to high molecular forces and low chain mobility in the PLA matrix as well as the low degree of polymerization. White vinegar, which contains linear carbo-carbon polymer chains also aided in increasing crystallization temperature.

3.3. Discussion of Results

Throughout the course of the research that was carried out on PLA, the impacts of a broad variety of different compositions of the components, as specified in connection with their loading, were explored.

In comparison to PLA by itself, the results of this study suggest that PLA blends have a stronger resistance to deformation and a more rigid character. When a tensile load is applied to the blend, the strong interphase contact between PLA and glycerol contributes to the high tensile strength and modulus of the blend. As a result of the increased interfacial adhesion between the chemical bonds that contributed to increased toughness, the level of plasticizer that was present in neat PLA decreased. Both S1 and S2 have shown significant increases in their tensile modulus, 5.7%, and 33.8% respectively.

The value of S3 has decreased by 2.85% as a direct result of an excess supply of liquids that contain hydroxyl and carboxyl groups. The tensile strength of S2 PLA and S3 PLA has both grown, with S2 seeing a 5.7% increase and S3 seeing a 23.46% increase. The higher tensile strength of PLA blends was attributed to an increase in the molecular weight of the polymer chain. This increases both tensile strength and the impact of the material. When a polymer chain is longer, it suggests that there are more entanglements of other polymer chains present along the chain, which results in greater strength at break.

Glycerol, a triol molecule with a 3-hydroxyl group that reacted with a carboxyl group and established a hydrogen link, in addition to an excessive amount of white vinegar in a solvent like water, led the PLA to forget its chemical structure. This was induced by the formation of hydrogen bonds. Despite this, the observed changes in the tensile modulus of the films were not as significant as those that occurred with the addition of an 8% glycerol blend. This suggests that oils and glycerol diminish the intermolecular tensions and increase the mobility of PLA chains, which ultimately results in an increase in the blend's adaptability. It has been reported that the plasticizing effect of glycerol on PLA films was due to the interaction between the hydroxyl groups and carboxyl groups in PLA and hydroxyl groups in glycerol and this was the mechanism that was responsible for the plasticizing effect. Because the function of plasticizer is to prevent the build-up of intermolecular forces along polymer chains, it is anticipated that increasing the amount of glycerol present in the PLA matrix will result in a decrease in the material's tensile modulus while simultaneously increasing its flexibility and elongation at break.

When compared to pristine PLA, the flexural modulus of S1, S2, and S3 PLA has increased by 13.90%, 24.66%, and 4.93%, respectively. The zeolite and glycerol in this case work together to act as a binding agent, and as a result, the stress transfer in the matrix was increased. This, in turn, caused an increase in the toughness elongation, as well as a higher flexural strain in the elongation, with respective averages of 86.32% and 44.19%. This is a tremendously favorable turn of events.

After including glycerol and oils in the PLA matrix, researchers observed an increase in the impact energy of the material. As a consequence of this, the impact energies of S1, S2, and S3 PLA are now 20 KJ/m², 20.95 KJ/m², and 21.06 KJ/m² respectively, whereas the impact energies of pristine PLA are 18.46 KJ/m². As a side note, the fact that the tensile modulus, flexural modulus, and elongation percentages all increased indicates that the matrix is doing an excellent job of transferring stress.

At this time, 5% - 15% zeolite and 1% - 3% green camphor, both of which have an appropriate porosity and are thermally stable, were causing the PLA to be thermally stable up to 345.57°C. This temperature is 0.58% lower than the temperature at which the neat PLA could be thermally stable. If these combinations were introduced in excessive proportions, it might make the substance more thermally stable. As a result of the addition of glycerol, zeolite, and green camphor, the PLA chain mobility was, to some extent, reduced, and the Glass transition temperature (T_g) was raised in S1, S2, and S3 PLA. Also, an increase in stiffness in the polymer matrix increases glass transition temperature. The presence of double bonds in glycerol and white vinegar, as well as aromatic and volatile green camphor, limited the flexibility of the polymer chain. This resulted in an increase in Melting temperature (T_m), which was caused by the strong intermolecular forces that were present with the combinations in the PLA matrix. In contrast to neat PLA, however, the crystallization phase (T_c) has increased in S1,

S2, and S3 PLA as compared to neat PLA. This is the result of increased molecular stresses, a lower degree of polymerization, and decreased chain mobility in the new PLA matrix.

Carom seed oil, eucalyptus, and clove oils have been used to reduce the risk of pathogen growth, especially in unprocessed food packages. This is especially true since carom seed oil is used to make clove oils. They have good antimicrobial properties that fight against *E. coli*, staphylococcus, and aspergillus. Moreover, it has been established that the addition of 1.5% or less of the PLA matrix does not affect the matrix's mechanical properties [34].

This correlates to a noticeable improvement in the material's mechanical properties. As a consequence of this, the blend in question can be considered an alternative to the PLA that is typically employed.

4. Conclusions

- Research on PLA examined the effects of different material compositions as indicated by their loading. Glycerol and oils were added, and PLA's impact, tensile strength, and tensile modulus gradually improved. Zeolite and glycerol act as binding agents, increasing matrix stress transfer and toughness elongation compared to pristine PLA.
- PLA is thermally stable at 345.57°C, 0.58% lower than neat PLA. It contains 5% - 15% zeolite and 1% - 3% green camphor, both thermally stable and porous. Combinations in excess percentages can improve thermal stability.
- Glycerol and green camphor reduced PLA chain mobility and raised the Glass Transition Temperature. Due to strong intermolecular forces in the PLA matrix, double bonds in glycerol, white vinegar, aromatic, and voltaic green camphor limited polymer chain flexibility, increasing Melting Temperature. Due to high molecular forces, low polymerization, and poor chain mobility, the new PLA matrix has increased crystallization.
- With their effective antimicrobial qualities against *E. coli*, staphylococcus, and aspergillus. Carom seed, Eucalyptus, and Clove oils have been utilized to lower the danger of pathogen growth, particularly in unprocessed food packages. It has also been shown that the mechanical properties of PLA matrix are unaffected by the addition of 1.5% by volume or low.

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Contribution from the Author

Vishal Atnurkar contributed to the original manuscript draft, data collection, and data synthesis. Jens Schuster assisted with the review of the report and re-

search process. The methodology approach was taken by Yousuf Pasha Shaik and Vishal Atnurkar. The supervision of Yousuf Pasha Shaik aided in the review of the report. The published version of the manuscript has been read and approved by all authors.

Data Availability Statement

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Conflicts of Interest

The authors declare no conflict of interest.

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