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Research article

Degradation profile of biocomposite antimicrobial packaging with bacteriocins: Implications for organic recycling

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Abstract. This study focused on developing compostable packaging materials possessing beneficial microbiological characteristics and evaluating their degradation process. We explore the use of nisin as a versatile antimicrobial additive in biodegradable materials. Our findings demonstrate nisin's significant influence on the processing and degradation of composites. Nisin's amphiphilic structure, characterized by both hydrophobic and hydrophilic components, enhances its interaction with the polymer matrix. This interaction affects smaller molar mass reduction during processing and leads to variations in degradation dynamics. The results suggest that nisin has minimal impact on the thermal stability of the matrix during processing, with less than a one-degree increase observed. Thermal stability improved for all materials during degradation, but nisin's presence slowed this increase. Nisin's influence on the matrix of jute fiber composites, was more pronounced, affecting the material during processing and subsequent degradation. The results indicate that samples containing nisin inhibit the growth of the gram-positive bacterium *Staphylococcus aureus* (*S. aureus*) after 24 h of incubation. The inclusion of fillers in composites elevates the microbiological activity by filler 'antibacterial promotion' effects in samples containing nisin. Connection with previous studies highlights the significance of polymer chain length on the composite's antimicrobial properties.

Keywords: *biocomposite, hydrolysis, poly(hydroxy alcanoate), biodegradation, composting, antimicrobial properties*

1. Introduction

Organic recycling is the process of breaking down organic materials like food waste and yard trimmings into compost or other reusable materials. By diverting organic waste from landfills and using it to create nutrient-rich compost, organic recycling helps reduce greenhouse gas emissions, fosters sustainable agriculture, improves soil health, and supports biodiversity. Embracing organic recycling practices is crucial for building a more circular and environmentally friendly food system [1, 2]. Utilizing compostable packaging and actively engaging in organic recycling practices not only reduces waste going to landfills but also contributes to a more sustainable and environmentally friendly approach to packaging and waste management. By choosing compostable materials for packaging and using organic recycling for its utilization, businesses and individuals can actively

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contribute to a circular economy and significantly reduce their carbon footprint. This shift towards more eco-friendly practices is essential for creating a healthier and more sustainable future for both people and the planet [3].

However, organic recyclable packaging, apart from its main advantage of reducing the amount of waste in landfills, may have other added values. The current scientific focus is on developing technologies that enable the controlled release of its components, utilizing encapsulation methods and natural active agents. This suggests a focused interest in developing efficient and targeted delivery systems, with potential implications for sectors like single-use food packaging [4]. Biodegradable bioactive composites with antimicrobial additives are highly coveted, as they offer a greener alternative to traditional materials. Their eco-friendly nature and antimicrobial properties make them a promising option where sustainability and hygiene are essential. This combination of characteristics makes these composites, not only attractive, but they are also beneficial for both the environment and human health [5]. The use of biodegradable polymers in this type of packaging enables the disposal of finished products through organic recycling. The addition of natural fillers lowers the price of the final product while maintaining its biodegradability, and the introduction of an antimicrobial substance significantly increases the application's versatility. However, the composites obtained in this way require detailed research because different types of polymer matrices, fillers, and additives, as well as their content, affect the properties of the final product.

Polyhydroxyalkanoates (PHAs) are currently being seen as potential substitutes for petrochemical plastics in a wide range of applications, due to their robust mechanical qualities. Often, these properties are comparable to those of thermoplastics derived from petroleum, but PHAs have the added value of being biodegradable [6]. Although PHAs have shown great potential as biodegradable plastics, their widespread industrial applications are hindered by high production costs. Research efforts are ongoing to address these challenges and make PHAs more cost-effective and versatile [7]. Reducing the production costs of the final products by introducing natural fillers is one of the ways of developing the PHA market.

With plastic pollution levels increasing, novel polymeric materials for packaging can not only maintain the functional properties of traditional plastic wrapping and biodegrade into biogenic compounds but also reduce harmful microbial growth on the products they protect when incorporated with antimicrobial agents. The incorporation of antimicrobial additives into biodegradable composites enhances their appeal as sustainable materials for various applications. These materials not only offer environmental benefits but also provide added functionality, making them more attractive to investors, researchers, and potential markets [8].

Antimicrobial properties of bio-composites can also be achieved by the incorporation of nisin. Nisin is a commercial bacteriocin produced by *Lactococcus lactis* (*L. lactis*) and it exhibits a broad inhibitory spectrum against a wide range of Gram-positive bacteria [9]. Nisin is a small 3.4 kDa peptide, that acts in the nmol/L range [10] and is produced as an inactive precursor, containing an *N*-terminal leader peptide that is cleaved after secretion by the subtilisin-like serine protease NisP [11]. It contains five specific lanthionine rings, of which the first two are important for Lipid II binding, and the last two are crucial for pore formation in the membrane [10]. The incorporation of nisin into materials such as food packaging has attracted interest due to nisin being recognized as 'safe for food preservation', and it is able to maintain its efficacy during heating processes [12].

This study investigates a range of composites containing natural fillers and nisin as an antimicrobial agent. Poly[(R)-3-hydroxybutyrate-*co*-4-hydroxybutyrate] (P(3HB-*co*-4HB) was used as a matrix for composites and as a reference material enabling the assessment of the impact of the presence of fillers on antimicrobial properties and degradation progress. The following microorganisms were used to assess the antimicrobial properties of the obtained materials: *S. aureus* and *Escherichia coli* (*E. coli*).

It is known that nisin exhibits antimicrobial effects on Gram-positive bacteria. However, research by Kuwano *et al.* [13] demonstrated that purified nisin can have antibacterial activity both against Gram-positive and Gram-negative bacteria. *S. aureus* was selected as a test species as it is a major human Gram-positive pathogen that is the cause of a range of infections. These infections include bacteraemia and infective endocarditis as well as osteoarticular, skin, pleuropulmonary, and device-related infections, making it an important and

suitable test-species for a composite with potential applications in medicine [14].

The Gram-negative bacteria *E. coli* is one of the most studied model microorganisms in biological sciences and it has displayed a great deal of phenotypic diversity [15]. This includes pathogenic isolates with multiple issues relating to public health. For these reasons, *E. coli* was applied to this study.

However, the presence of nisin may also influence the degradation progress of materials containing it. Since organic recycling is the proposed disposal method for these materials, this impact should be determined. Therefore, degradation tests were conducted under both composting conditions and, for comparison, in a laboratory setting to assess abiotic degradation. The results obtained from these tests will allow for the design of compostable packaging with microbiological properties.

2. Materials and methods

2.1. Materials

The commercially available P(3HB-*co*-4HB) powder, with a number-average molar mass of M_w = 220 000 g/mol and a molar mass dispersity of M_w/M_n = 2.3, containing 8% of 4-hydroxybutyrate (4-HB) units (calculated by proton nuclear magnetic resonance spectroscopy), obtained from Tianjin GreenBio Materials (Tianjin GuoYun Biological Material Co. Ltd., Tianjin, China) was used as the polymer matrix. Wood flour (Jeluxyl WEHO 500S) from JELU-WERK (Rosenberg, Germany) supplied by Brenntag (Essen, Germany) and jute (F-501/050) from Schwarzwälder Textil-Werke (Germany) were employed as natural fillers. Before mixing and processing, both fillers were dried for 4 h at 80 °C in a universal oven UF55 (Memmert GmbH + Co. KG, Schwabach, Germany). To achieve antimicrobial properties, the B-Nisin-2 from Novazym Poland (Wielkopolska Centre of Advanced Technologies, Poznań, Poland) were used.

2.2. Processing

The composites were effectively prepared using a micro-extruder MiniLab II (Thermo-Haake, Austin, TX, USA) equipped with corotating twin-screws, with a screw rotation rate of 100 rpm, and then the bone shapes were formed using a MiniJet II (Thermo-Haake, Austin, TX, USA) mini-injection molding machine with a mold temperature of 60 °C. The processing parameters for all samples were the same respectively: temperature of plasticizing zone – 140 °C, injection temperature – 140 °C, and injection pressure – 300 bar. This method is likely to have ensured the correct blending and shaping of the materials for the desired composite outcome. The composites were formulated with 15 wt% of filler and 2 wt% of nisin.

2.3. Antimicrobial testing

The antimicrobial testing for the activity for the range of P(3HB-*co*-4HB) and P(3HB-*co*-4HB) composites with and without 5 wt. % nisin was investigated against the Gram-positive strain *S. aureus* (NCIMB 6571) and Gram-negative *E. coli* (K12W-T) using discs/or similar mass-section diffusion assays in triplicate. The microbial strains were obtained from the University of Wolverhampton culture collection. Organisms were maintained at –20 °C in a lyophilized form. Stock cultures of *S. aureus* and *E. coli* were resuscitated on sterile tryptone soy agar (TSA) (Sigma-Aldrich, Saint Louis, MO, USA) and incubated for 48 h at 37 °C. Overnight broth cultures were aseptically prepared using the stock plates. Using sterile forceps, the discs and cut sections were placed on TSA plates that were spread with overnight microbial cultures, following incubation at 37 °C for 24 h. Tetracycline (Oxoid, UK) discs and blank paper discs were used as controls. All these experiments were performed three times, and all results were expressed as an average of three replicates (in mm).

2.4. Degradation tests

Degradation tests were performed to assess the stability of the materials under two different scenarios: composting conditions in an industrial composting pile and hydrolytic degradation in demineralized water at an elevated temperature of 70 °C [5]. These methods aimed to simulate real-world environmental conditions to evaluate the materials' breakdown processes effectively.

2.5. Characterization of the samples

2.5.1. Visual examination

The scanning electron microscopy (SEM) analysis of the materials was carried out using the Quanta 250 FEG high-resolution environmental scanning electron microscope (FEI Company, Fremont, CA, USA) at an acceleration voltage of 10 kV. The samples were observed without coating under a low vacuum

of 80 Pa, allowing for a detailed examination of the surface characteristics and morphology of the materials. This method offers valuable insights into the microstructure and composition of the samples.

2.5.2. Gel permeation chromatography (GPC) analysis

The samples were analyzed using the GPC method to determine their molar mass and molar mass dispersity. The samples were dissolved in chloroform at a concentration of 0.3% w/v, the Nexera HPLC/UHPLC Pump LC-40DXR (Shimadzu, Kyoto, Japan) was used, which passed the sample through two Mixed C Styragel columns and a refractive index detector Shodex SE 61 (Showa Denko, Munich, Germany). A calibration curve was created using narrow molar-mass dispersity polystyrene standards from EasiCal Pre-prepared Calibration Kits (Kit S-M-10, Polymer Laboratories, Church Stretton, UK) to accurately determine the molar mass distribution of the polymers.

2.5.3. Thermal properties

The thermal characteristics of the samples were analyzed using a TGA/DSC1 Mettler-Toledo (Columbus, OH, USA) thermal analyzer and a TA DSC Q2000 apparatus (TA Instruments, Newcastle, DE, US). The TGA/DSC1 analyzed the samples up to 800 °C at a heating rate of 10 °C/min in a nitrogen stream, while the DSC studies were performed using a heating rate of 20 °C/min from –80 to 200 °C. The instrument was calibrated with high-purity indium, and experiments were carried out under a nitrogen atmosphere with a flow rate of 50 mL/min. The second heating run from –80 to 200 °C was conducted on samples rapidly cooled from melt to determine the glass transition temperature, with the sample being amorphous after rapid cooling from 200 °C.

2.5.4. Fourier transform infrared spectroscopy (FTIR)

To analyze changes in the material's structure and surface, FTIR spectroscopy was conducted using a high-resolution FT/IR-6000 Jasco instrument (Jasco Corporation, Tokyo, Japan). Spectra were collected over a broad range from 4000 to 200 cm^{-1}, with a resolution of 4 cm^{-1}, and an average of 64 scans were used to ensure data accuracy and reliability.

2.5.5. Nuclear magnetic resonance (NMR) measurements

The ^{1}H NMR spectra were acquired using a Bruker Avance spectrometer (Fremont, CA, USA) with specific parameters: 64 scans, 11 μs pulse width, and a 2.65 s acquisition time. Operating the spectrometer at 600 MHz with tetramethylsilane (TMS) as the internal standard and $CDCl_3$ as the solvent ensures accurate chemical shift referencing and a stable environment for NMR analysis.

3. Results and discussion

FTIR spectroscopy was used to investigate the interaction between nisin and other fillers with P(3HB-*co*-4HB). For the nisin, three characteristic absorption peaks at approximately 1630, 1518, and 1240 cm^{-1} in the spectrum are observed, which correspond to amide I, amide II, and amide III bands, respectively, and are assigned to the secondary structure of peptides [16]. For wood flour and jute fibers on the FTIR spectra, the C–H stretching vibration of hemicellulose and pectin at 1509 and 1503 cm^{-1}, acetyl groups of lignin at 1261 and 1239 cm^{-1}, and C–O/C–C stretching vibration at 1026 and 1025 cm^{-1} were found respectively [17, 18]. The spectrum of the pure matrix shows absorbance peaks as following at 1719 cm^{-1} (C=O stretching), 1274 cm^{-1} (C–O–C stretching), 1129 cm^{-1} (C–O stretching of –CH–O– moiety) and 1045 cm^{-1} (C–O of the O=C–O moiety) [19–21]. The results (Figure 1) indicate that the addition of nisin and/or other fillers did not have a notable impact on the structure of the materials being studied.

3.1. Antimicrobial properties

In this experiment, two microorganisms, *E. coli* K12W-T and *S. aureus* (NCIMB 6571), were tested. The obtained results for samples containing nisin after 24 h of incubation showed a positive result only against gram-positive *S. aureus* (Table 1). This was as expected, as nisin is a bacteriocin produced by *L. lactis* for the inhibition of Gram-positive bacterial species [9]. The observation in our previous study [5] that nisin shows reduced microbiological activity in a composite with wood flour at higher molar mass indicates that the molecular weight of the matrix plays a crucial role in the effectiveness of antimicrobial products. This suggests that optimizing the matrix

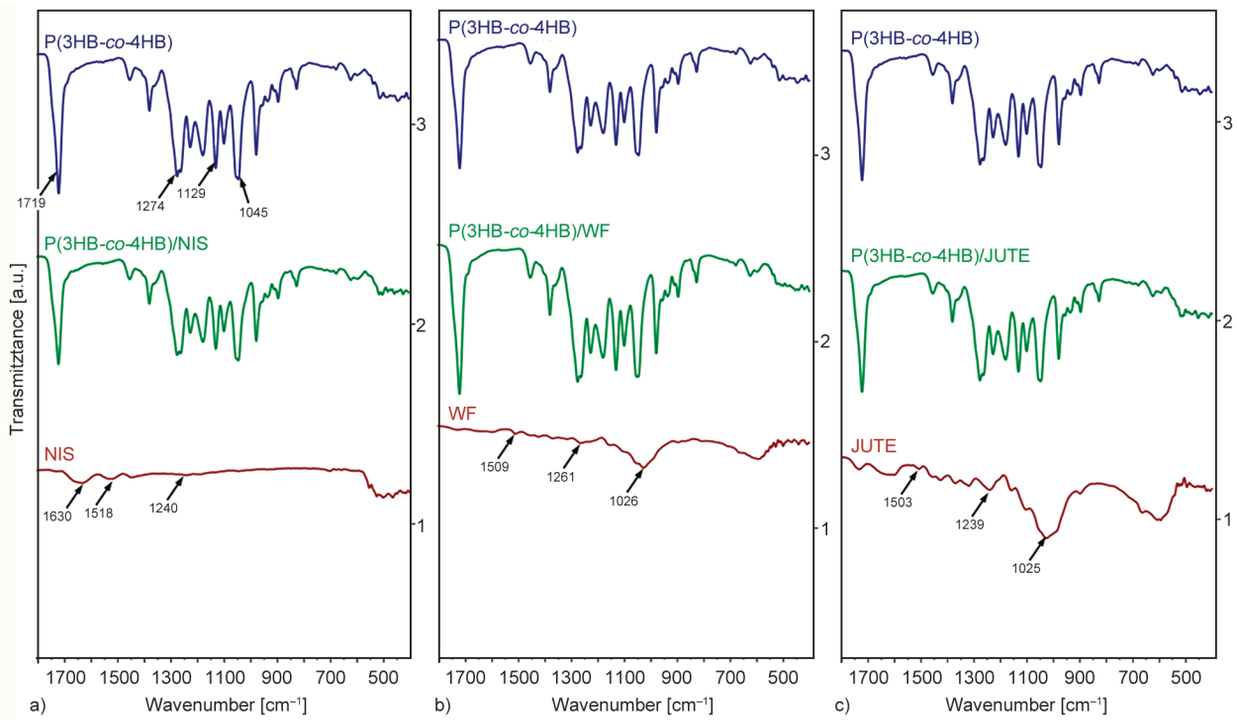

Figure 1. Selected representative FTIR spectra of the P(3HB-*co*-4HB) with nisin (a), wood flour (b), and jute fibers (c).

Table 1. Results for antimicrobial testing against *E. coli* and *S. aureus*. Results (average of 3 replicates) are presented as a zone of inhibition (ZOI) [mm] after 24 h of incubation at 37 °C.

Sample	*S. aureus* ZOI [mm]	*E. coli* ZOI [mm]
P(3HB-*co*-4HB)	Not detected	Not detected
P(3HB-*co*-4HB)/NIS	1.1±0.1	Not detected
P(3HB-*co*-4HB)/WF	0.5±0.1	Not detected
P(3HB-*co*-4HB)/WF/NIS	1.2±0.1	Not detected
P(3HB-*co*-4HB)/JUTE	0.5±0.1	Not detected
P(3HB-*co*-4HB)/JUTE/NIS	1.9±0.1	Not detected
Blank	Not detected	Not detected
Tetracycline	10±1	12±1

composition, particularly its molar mass, could enhance the release and activity of nisin, thereby improving its antimicrobial properties in such formulations.

Antimicrobial testing against the Gram-negative strain of *E. coli* revealed a lack of activity for all composite samples. However, both pathogenic microbes exhibited antimicrobial activity when tested with tetracycline.

Without nisin, P(3HB-*co*-4HB)/JUTE seemed to have limited antimicrobial activity. In addition, P(3HB-*co*-4HB)/WF also showed a small inhibition area from the test samples. Some antimicrobial activity was expected for samples with WF due to filler content. Studies indicate that various wood species possess inherent antimicrobial properties, which can inhibit the growth of bacteria [22]. Additionally, wood flour has been suspected of having 'antibacterial promotion' effects on certain compounds, such as triclosan/PLA blends, boosting efficacy [23]. When P(3HB-*co*-4HB) samples were used, there was no antimicrobial activity at all, showing the wood and jute components did have an anti-bacterial effect.

3.2. Degradation study

Changes in P(3HB-*co*-4HB) matrix composition in neat P(3HB-*co*-4HB) and P(3HB-*co*-4HB) composites with the addition of nisin during incubation in both mediums were investigated using ^{1}H NMR analysis for specimens after selected incubation periods. The ^{1}H NMR spectrum of P(3HB-*co*-4HB) before degradation showed signals corresponding to the protons of P3-HB constitutional repeating units (signals **1–3**) and signals corresponding to the protons of P4-HB constitutional repeating units (signals **4–6**) (Figure 2).

Generally, no changes in the composition of the copolymer were observed during degradation, regardless of the additive and/or fillers used and the type of degradation medium. The presence of the additives used affects the degradation rate, as evidenced by changes in molar mass (Table 2), but does not affect the composition of the matrix. After 21 days of incubation in all environments and for all

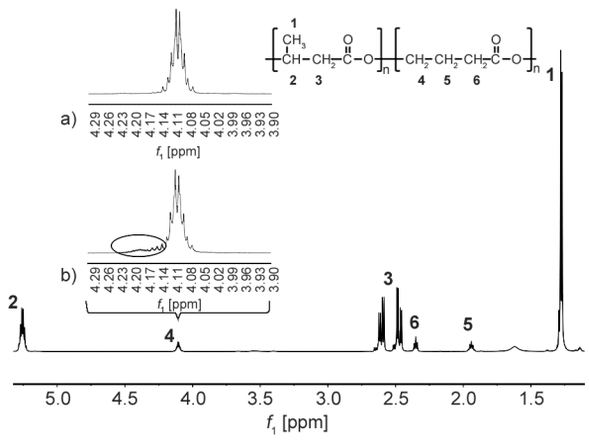

Figure 2. [1]H NMR spectrum of neat P(3HB-*co*-4HB) before degradation. Enlargement of a part of the spectrum of neat P(3HB-*co*-4HB) before degradation (a) and after 21 days of incubation in water at 70 °C (b).

compositions, additional signals originating from oligomer end groups formed during degradation are observed (Figure 2b).

The incorporation of fillers and nisin into the polymer matrix resulted in changes to the molar masses of the samples during processing and degradation testing (Table 2). This alteration in molar mass provides valuable information about the differences in the degradation progression of the materials when various additives were used.

The usually higher moisture content of jute fibers [24] compared to wood flour [17] indicates a greater ease with which it absorbs water. This property played a significant role during processing. Both fillers were subjected to the drying process in the same way, but the reduction in molar mass for the composite with jute is higher by approximately 10% compared to the reduction in molar mass during the processing of pure matrix and composite with wood flour. This phenomenon may result from the presence of a small amount of water in jute fibers, leading to greater degradation of the material at elevated temperatures during processing. However, the addition of nisin completely reverses this relationship (Table 2). The adsorption of proteins and peptides on surfaces can result in significant changes in their conformation, orientation, and interactions, depending on the surface properties. Nisin orients by its hydrophobic side on the hydrophobic surface and by its hydrophilic side exposed to the surrounding environment [25]. As PHAs are hydrophobic in nature [26, 27], the presence of nisin in the composite combined with the hydrophobic matrix may limit the

Table 2. Molar mass (M_w) and dispersity (M_w/M_n) before and after degradation in different environments of neat P(3HB-*co*-4HB) and P(3HB-*co*-4HB) based composites.

P(3HB-*co*-4HB)/filler	Time [days]	M_w [g/mol]	M_w/M_n
		without nisin/with nisin	
P(3HB-*co*-4HB)	0	113 000/116 000	2.4/2.6
	7	69 000/74 000	2.3/2.3
	21	23 000/24 000	2.2/2.2
	42	18 000/24 000	2.3/2.2
	21 compost	15 000/18000	2.3/2.2
P(3HB-*co*-4HB)/WF	0	114 000/139 000	2.7/2.4
	7	75 000/89 000	2.4/2.3
	21	21 000/25 000	2.2/2.2
	42	21 000/25 000	2.2/2.2
	21 compost	16 000/28 000	2.2/2.3
P(3HB-*co*-4HB)/JUTE	0	93 000/155 000	2.1/2.6
	7	68 000/97 000	2.2/2.5
	21	36 000/56 000	2.2/2.2
	42	13 000/19 000	2.1/2.3
	21 compost	20 000/20 000	2.2/2.3

access of the small amount of water present in the filler to the polymer during processing. The effect of the presence of nisin is also visible during hydrolytic degradation. The same tendency is maintained there and the reduction in the molar mass of samples with nisin is smaller than for samples without nisin degraded under the same conditions (Table 2). The mass loss of the samples during hydrolytic degradation is about 6% after 42 days for all samples without nisin and for the P(3HB-*co*-4HB)/NIS sample. However, composite samples with nisin showed about 10% mass loss after the same time. This may also be due to the nature of nisin [25], which, by hindering water's access to the polymer, may cause its better penetration into the filler, facilitating sample disintegration.

However, the situation is different during the degradation of composite with jute fibers in compost, where, in addition to moisture, we are dealing with the presence of microorganisms. The presence of a more water-absorbing filler may enable faster colonization by microorganisms that accelerate matrix degradation [28, 29]. This is confirmed by SEM photos, where practically the entire surface of the P(3HB-*co*-4HB)/JUTE and P(3HB-*co*-4HB)/JUTE/NIS samples were covered with numerous pinholes after 21 days of incubation in compost (Figure 3).

Unlike with jute and wood flour, the thermal stability of the matrix remains almost unchanged during processing, with a slight increase of less than one degree when nisin is present (Table 3). However, an

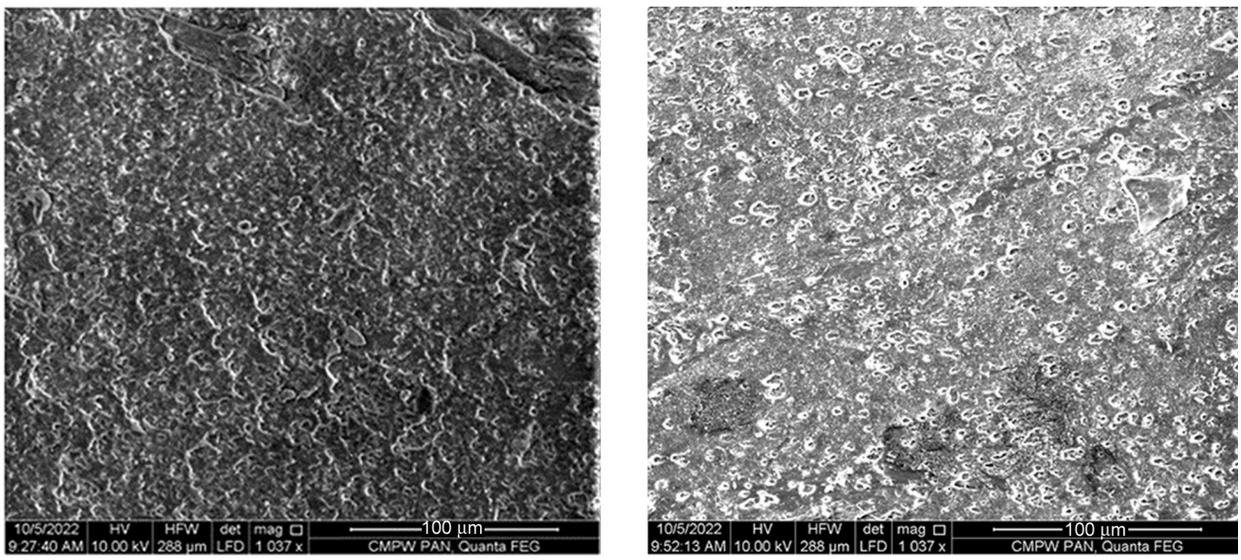

Figure 3. SEM micrographs of the P(3HB-*co*-4HB)/JUTE after 21 days incubation in composting conditions, without nisin (a) and with 2 wt% of nisin (b).

increase in thermal stability during degradation was observed. This phenomenon could be influenced by the presence of acidic low-molar-mass degradation products or acidic components released from fillers, aligning with previous data [5]. The presence of nisin caused, despite the overall increase in maximum decomposition temperature (T_{max}) during degradation in this case, it was slightly slowed down in comparison to composites with only fillers.

In the initial stage of degradation in water at 70 °C, a decrease in melting enthalpy (ΔH_m) was observed for all materials (Table 3). The effect may be related to the samples staying at elevated temperatures, causing the melting of unstable crystals which increases the amorphous scattering [30]. In further stages of degradation, an increase in ΔH_m was observed, caused by further degradation of the material and the formation of molecules with a lower molar mass, which facilitates their crystallization [31]. However, for the jute composite, the ΔH_m increases again later, which coincides with a smaller decrease in the molar mass (Table 2) of the samples after this time compared to other compositions.

The DSC traces exhibited an increase in the number of multiple melting endotherms for the P(3HB-*co*-4HB)/NIS sample before degradation in comparison to the neat matrix sample. This is probably caused by the nucleation effect due to the presence of nisin. The multiple melting endotherms observed are a consequence of the balance between the melting and recrystallization and the lamella thickness distribution existing within the sample, prior to heating [32]. The same phenomenon is observed in the case of an addition of any filler in composites [5]. The addition of nisin and fillers resulted in an increase in the glass transition temperature of the matrix, also observed during degradation. This indicates the occurrence of physical entanglement [33, 34].

4. Conclusions

This research was conducted on biodegradable materials to assess the impact of using nisin as an antimicrobial additive and it revealed clear differences between the material samples. These differences were evident at the processing stage, where the presence of nisin limits the reduction in molar mass to varying degrees, depending on the filler used. The difference in molar mass of the pure matrix without and with nisin was 3%. In the case of composites with wood flour and jute, this difference was 18 and 40%, respectively, indicating a clear reduction in matrix degradation during processing in the presence of nisin. For composites containing jute fibers, which have a greater tendency to absorb moisture, the presence of nisin had a greater impact on changes in the matrix, both during processing and throughout degradation. This effect is due to the behavior of nisin, resulting from its structure. Nisin's hydrophobic side chain is attracted to hydrophobic surfaces, while its hydrophilic side is exposed to the surrounding environment. This interaction may be crucial for its antimicrobial activity and the degradation rate of the polymer

Table 3. Calorimetric parameters of P(3HB-*co*-4HB) and P(3HB-*co*-4HB) based composites before and after degradation.

Sample name	Time [days]	T_{max} [°C]	R_{d600} [%]	T_g [°C]	T_m [°C]	ΔH_m [J/g]
P(3HB-*co*-4HB)	0	245.4	3.0	–11.2	146.8	58.8
	7	271.7	1.4	–1.1	100.4/141.0/150.8	58.0
	21	289.8	1.1	–2.8	142.1/161.6	80.4
	42	295.6	0.9	–3.0	143.1/149.4	63.8
	21 compost	286.4	1.3	–3.2	144.5/161.6	74.6
P(3HB-*co*-4HB)/NIS	0	245.7	8.0	–4.7	121.2/142.4/148.7	59.3
	7	265.3	2.0	–2.7	99.6/147.1/163.4	57.0
	21	281.4	1.2	–3.9	104.2/129.7/138.6/154.0	96.8
	42	281.0	1.2	–2.19	102.6/141.9/148.7/163.0	66.8
	21 compost	276.9	1.6	–4.7	121.2/142.4/148.7	59.3
P(3HB-*co*-4HB)/WF	0	247.5/320.9	6.3	–2.0	144.1/148.2	66.0
	7	281.2/358.5	4.7	1.1	102.0/136.8/149.2/164.0	63.5
	21	294.5/368.7	4.1	–3.9	71.0/115.6/135.3/142.4/153.5/161.2	79.2
	42	294.4/367.6	4.1	–2.0	133.5/144.6/162.4	46.0
	21 compost	275.5/346.7	4.9	–3.8	109.3/134.4/143.0/161.0	60.7
P(3HB-*co*-4HB)/WF/NIS	0	248.3/323.1	11.1	–2.0	137.1/146.2	80.8
	7	273.7/348.6	4.6	0.5	103.5/137.1/147.7/159.0	37.9
	21	286.3/364.2	4.4	–1.3	112.5/140.5/146.5	40.4
	42	286.9/365.6	4.5	–1.1	136.6/147.0/163.5	41.6
	21 compost	270.8/336.1	5.9	–2.3	110.4/145.8/164.3	67.9
P(3HB-*co*-4HB)/JUTE	0	248.0/328.3	6.0	–7.0	76.8/131.9/145.8/161.3	76.6
	7	280.7/357.9	4.5	–0.6	97.7/135.3/145.7/162.1	35.2
	21	291.9/365.8	4.4	–1.4	101.3/134.0/146.3/162.7	35.1
	42	295.8/367.3	3.5	–4.0	135.3/143.7/160.5	52.9
	21 compost	267.3/343.5	4.7	–1.9	68.9/138.3/147.1/161.9	61.4
P(3HB-*co*-4HB)/JUTE/NIS	0	248.8/331.3	11.0	–2.7	70.2/135.8/144.4/152.1	56.2
	7	279.0/356.9	3.9	0.5	103.5/140.3/151.9	39.6
	21	283.9/359.2	4.2	–0.4	105.8/138.9/152.3/167.3	36.2
	42	289.7/364.6	2.8	–3.4	112.4/147.3/166.5	58.0
	21 compost	273.2/340.2	5.2	–4.3	77.9/139.8/148.2/164.8	69.0

T_{max} – maximum decomposition temperature,
R_{d600} – residual mass at 600 °C,
T_m – melting temperature,
ΔH_m – melting enthalpy (first heating scan, 20 °C/min),
T_g – glass transition temperature (second heating scan after rapid cooling, 20 °C/min.

matrix. The presence of fillers in composites increases the microbiological activity of samples containing nisin when compared to the pure matrix. Moreover, comparing the results with our previous studies, we observed a notable correlation between the molar mass of the matrix and the antimicrobial efficacy of nisin-containing materials.

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