

Tuning Antibacterial and Physical Properties of Biodegradable Polymer Systems Incorporating Carvacrol

Luigi Botta,* Maria Chiara Mistretta, Vincenzo Titone,* Silvia Russello, Giuliana Garofalo, and Raimondo Gaglio

The addition of antimicrobial additives in packaging systems is becoming essential, and this study aimed to incorporate carvacrol (CRV) into Poly(lactic acid) (PLA)/Poly(butylene adipate-co-terephthalate) (PBAT) blends to investigate the effects of blend composition on the resulting material's properties, with a particular focus on CRV release kinetics and antibacterial activity. The materials are prepared via melt mixing and compression molding and are thoroughly characterized through mechanical, rheological, and wettability analyses. Tensile tests reveal that adding PBAT to PLA increases flexibility, reducing modulus by 26% and tensile strength by 60%, while elongation at break rises by 550%. Adding PLA to PBAT increases stiffness, with modulus rising by 128%, but tensile strength and elongation decrease by 62% and 70%, respectively. The CRV release profile revealed that the release rate can be modulated by altering the blend composition. In vitro evaluation of antibacterial activity shows that the polymers with high PBAT content and containing CRV inhibited the growth of *Listeria monocytogenes* to undetectable levels ($<1 \text{ Log CFU mL}^{-1}$). Overall, the results show that the blend formulation significantly influenced the material properties compared to the pure components, providing effective antibacterial activity against both pathogens.

the issue of polymer pollution. Various strategies have been proposed to reduce waste and environmental impact. These include rethinking consumption habits, improving recycling, and adopting greener alternatives to petroleum-based plastics.^[4] Biodegradable polymers emerge as one of the most promising solutions in combating plastic pollution. These materials offer an environmentally friendly alternative to traditional plastics, which, due to their slow decomposition, can persist in the environment for hundreds of years, generating pollutants that cause significant harm to nature.^[5–8] However, biodegradable materials often have weaker properties than petroleum-derived polymers. Consequently, a viable solution is biodegradable blends.^[9–12]

Biodegradable blends enable the attainment of physical and chemical properties superior to those of individual polymers.^[13,14] In fact, the ability to combine different properties to obtain a material that meets specific application

1. Introduction

Plastic pollution is an increasingly urgent global problem.^[1–3] Therefore, sustainability has become a key concept in addressing

needs, thus exhibiting superior performance compared to the individual constituent polymers, is one of their main advantages. Furthermore, optimizes material use, reducing costs without compromising functionality.^[15–17]

In parallel, another innovative strategy to enhance biodegradable polymers is the incorporation of essential oils.^[18–20] In fact, blending polymers with essential oils represents an innovative idea for developing sustainable food packaging materials. In particular, essential oils are known for their antibacterial and antifungal properties, which can inhibit the growth of bacteria and fungi on product surfaces, thereby enhancing the shelf life.

Carvacrol, a natural phenol found in oregano (*Origanum vulgare*), thyme (*Thymus vulgaris*), and savory, has gained increasing attention.^[18,21] It is widely used as a flavoring agent and a natural preservative due to its strong antimicrobial activity against bacteria, fungi, and viruses. Carvacrol inhibits spoilage microorganisms, helping to maintain food freshness and quality. This makes it highly suitable for food packaging applications.^[18,22,23]

Recently, the literature reports several studies on biodegradable matrices, including commercial blends with unknown compositions, incorporating additives with antimicrobial properties.^[18–20] However, to the best of our knowledge, no studies have investigated how the blend composition affects

L. Botta, M. C. Mistretta, V. Titone, S. Russello
 Department of Engineering
 RU INSTM
 University of Palermo
 Viale delle Scienze, Palermo 90128, Italy
 E-mail: luigi.botta@unipa.it; vincenzo.titone@unipa.it
 G. Garofalo, R. Gaglio
 Department of Agricultural
 Food and Forest Sciences
 University of Palermo
 Viale delle Scienze, Bldg. 5, Palermo 90128, Italy

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/mame.202500013>

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Table 1. Main properties of PLA and PBAT.

	Density, g cm ⁻³	M.F.I., g 10min ⁻¹	Mn, g mol ⁻¹
PLA	1.24	7 ^{a)}	1.03 × 10 ⁵
PBAT	1.26	2.7–4.9 ^{b)}	24 400

^{a)} 210 °C at 2.16 Kg; ^{b)} 190 °C at 2.16 Kg.

the material's properties in terms of release and antimicrobial activity.

Therefore, the aim of the present work was to study the effect of formulation on the properties, release kinetics, and antibacterial activity of a biodegradable blend, commonly used for packaging applications, incorporating carvacrol. Specifically, rheological, mechanical, and wetting behavior, as well as release properties and antibacterial activity, were investigated. The antibacterial properties of the biodegradable polymers were evaluated in vitro against two food-borne pathogenic bacteria (*Listeria monocytogenes* and *Salmonella Enteritidis*) using a combined microbiological approach based on the disc diffusion and the plate count method.

2. Experimental Section

2.1. Materials

The materials used in this work are a commercially available poly(lactide) (PLA) and poly(butylene adipate-co-terephthalate) (PBAT), known as Ingeo 4032D (NatureWorks, USA) and Ecoflex FC1200 (BASF, Germany), respectively. **Table 1** shows the main properties of the two materials.

Carvacrol (CRV), an antimicrobial agent, was purchased from Sigma–Aldrich (Sigma–Aldrich, USA).

2.2. Preparation

The materials were prepared with a Brabender mixer mod. PLE330 (Brabender, Duisburg, Germany) operating at 180 °C at 60 rpm for 5 min. The formulations are shown in **Table 2**.

CRV loading was added after 4 min during the process to minimize evaporation, see **Figure 1**. Before blending, to prevent hydrolysis phenomena,^[24] PLA and PBAT were dried in a vacuum oven overnight at 60 °C.

All samples used to determine properties were prepared by compression molding in a Carver laboratory hydraulic press

Table 2. Formulation of all samples investigated.

Sample code	PLA, %wt	PBAT, %wt	CRV, phr
PLA	100	–	–
PBAT	–	100	–
PLA/CRV	100	–	20
PBAT/CRV	–	100	20
75/25	75	25	–
25/75	25	75	–
75/25/CRV	75	25	20
25/75/CRV	25	75	20

(Carver, Wabash, IN, USA) at a temperature of 180 °C and a mold pressure of 300 psi for ≈3 min. To avoid loss of CRV due to evaporation during storage steps, all systems with CRV were stored at 4 °C and characterized within 24 h after preparation. **Figure 1** illustrates the processes used in this work.

2.3. Characterizations

2.3.1. Rheological Characterization

Rheological measurements were performed on ARES G2 rotational rheometer using 25 mm parallel plates at temperatures of 180 °C with a gap of ≈1.5 mm between the plates. The storage modulus, loss modulus, and complex viscosity were measured as a function of frequency (0.1–100 rad s⁻¹) within the linear viscoelastic regime of the sample. 5 tests were performed for each system with a reproducibility of ±5%.

2.3.2. Mechanical Characterization

Tensile tests were performed according to ASTM D638-14^[25] using an Instron universal testing machine (Instron, mod. 3365, High Wycombe, UK). The specimens were cut into rectangular shape with dimension of 90×10×0.5 mm.

The tests were performed with a crosshead speed of 1 mm min⁻¹ up to 3% strain. Thereafter, the crosshead speed was increased to 100 mm min⁻¹ until the specimen ruptured. The values of the Elastic modulus, tensile strength, and elongation at break are average of at least eight measurements. The tests were carried out as average of 10 tests, with a good reproducibility (±6%).

2.3.3. Morphological Analysis

Scanning electron microscope (SEM) images were acquired using a Phenom proX (Phenom World, Eindhoven, Netherlands). Prior to imaging, the samples were cryogenically fractured in liquid nitrogen.

2.3.4. Surface Analysis

Water contact angle (WCA) measurements were carried out using a First Ten Angstrom (USA) FTA1000C system, with demineralized water. At least 5 droplet images from each sample were analyzed, with a good reproducibility (±5%).

2.3.5. Spectroscopical Analysis

FTIR attenuated total reflection (FTIR-ATR) spectra were collected using a Perkin-Elmer FT-IR spectrometer (Perkin-Elmer, Norwalk, CT, USA) equipped with a single-reflection diamond ATR (Perkin-Elmer, Norwalk, Connecticut, USA). Spectra were collected in the range 4000–400 cm⁻¹, with an optical resolution of 4 cm⁻¹; the registered spectrum was the mean of 16 scans, and was executed in 3 min.

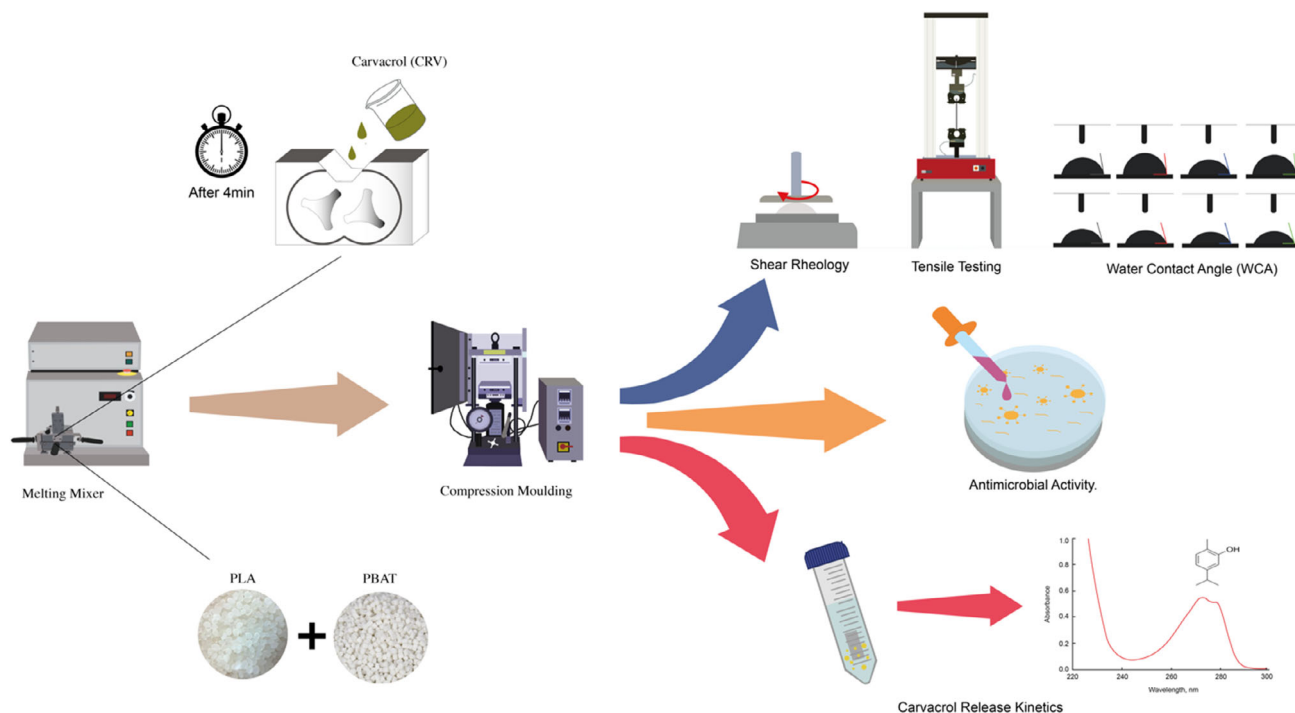


Figure 1. Scheme of the methodology adopted in this work.

2.4. Carvacrol (CRV) Release Kinetics

Release tests were performed by immersing a pre-weighed sample (20×20 mm square, weight≈100 mg) in 10 mL of distilled water at 4 °C and monitoring the absorbance of carvacrol at 273 nm^[26] at different time points by UV–vis spectroscopy, performed in a Specord 252 UV–vis spectrophotometer (Analytik Jena, Jena, Germany). Spectroscopic data were converted to concentrations using a calibration line, constructed according to our previous work.^[18] After each time measurement, the samples were immersed in 10 mL of fresh distilled water at 4 °C. The tests were carried out on three samples for each system, with reproducibility ensured. The graphs show the cumulative CRV release assessed by sequentially adding the CRV released after each time point.

2.4.1. Bacterial Strains and Growth Conditions

The strains *L. monocytogenes* ATCC19114 and *S. Enteritidis* ATCC13076 belonging to the American Type Culture Collection (ATCC) were used as indicator microorganisms (sensitive to antimicrobial compounds) toward of PLA, PBAT, and their blends with CRV. These bacteria were propagated in Brain Heart Infusion (BHI) (Oxoid Basingstoke, England) and incubated for 24 h at 37 °C.^[21]

2.5. Evaluation of Antibacterial Properties on Solid and Liquid Media

The antibacterial properties of the polymers were evaluated in vitro on solid and liquid media through the disc diffusion and

the plate count method, respectively. For the disc diffusion procedure, the approach given in ref. [18] was followed. Briefly, water agar plates (2% w/v) were overlaid with 7 mL of BHI soft agar (0.7% w/v) medium, previously inoculated at the final concentration 10⁷ CFU mL⁻¹ of each indicator strain. Once the soft agar was solidified, discs of 0.6-cm diameter of each sample were placed on the surface of the double agar layer. Sterile paper discs (Whatman qualitative filter paper, Grade 1) of the same diameter soaked with 10 µL of sterile water and streptomycin (10% w/v) (Sigma–Aldrich, Milan, Italy) were used as negative and positive control, respectively. Antibacterial activity was assessed by measuring the diameter of the inhibition zone around the discs with a digital caliper (Stainless Hardened, Farnell, Poland). The evaluation of inhibitory activity of polymers was also evaluated in liquid medium as described elsewhere^[27] Each indicator strains were inoculated at the final concentration of 10⁴ CFU mL⁻¹ into 20 mL volume sterile cups (Biogenerica Srl, Pedara, Italy) containing 10 mL of BHI and 2 discs (2-cm diameter) of each material. The cups were incubated at 37 °C and the antibacterial activity was evaluated soon after inoculation (0 d) and after 1 and 3 d of incubation. Microbial cell suspensions were firstly serially diluted and then spread plated^[28] on *Listeria* Selective Agar Base (LSAB) supplemented with SR0140E (Oxford) for *L. monocytogenes*; and on Xylose Lysine Deoxycholate (XLD) agar (Liofilchem, Roseto degli Abruzzi, Italy) for *S. Enteritidis*. All measurements regarding disc diffusion and plate count were carried out in duplicate.

2.6. Statistical Analysis

A one-way ANOVA analysis, followed by Tukey's test with a significance level of $p < 0.05$ was performed for pairwise

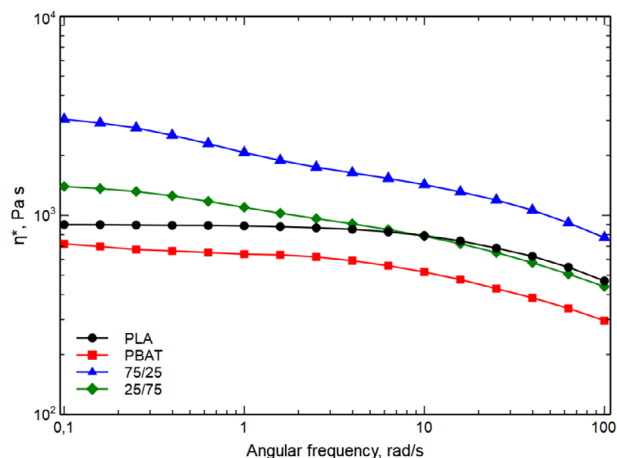


Figure 2. Complex Viscosity, η^* , as a function of angular frequency of PLA, PBAT, and their blends.

comparisons. All statistical analyses were carried out using XL-Stat software version 7.5.2 for Excel (Addinsoft, NY, USA).

3. Results and Discussion

3.1. Rheological, Mechanical, and Surface Characterization

Figures 2 and 3 show the complex viscosity, η^* , of PLA, PBAT, and their blends with and without carvacrol, respectively.

Both PLA and PBAT exhibit a Newtonian plateau at low frequencies and shear thinning behavior at higher frequencies, with PLA showing higher viscosity values than PBAT across the entire frequency range under examination. Conversely, the flow curves of the blends do not display a Newtonian plateau at low frequencies but rather exhibit slight shear-thinning behavior, with more pronounced non-Newtonian characteristics at higher frequencies. Moreover, viscosity values are higher than those of the individual components. Generally, the complex viscosity curves of the blends should fall between those of the two pure polymers.^[29,30] In this case, according to the scientific literature,^[31] the addition

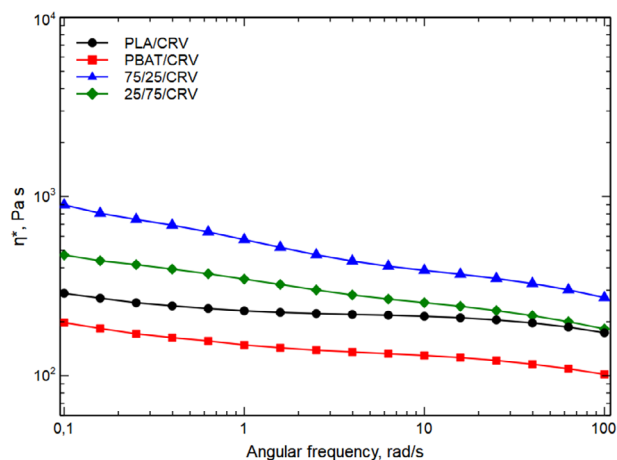


Figure 3. Complex Viscosity, η^* , as a function angular frequency of PLA, PBAT, and their blends with add Carvacrol.

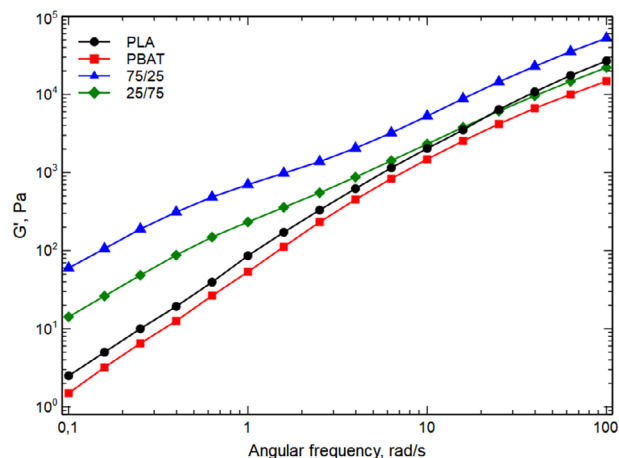


Figure 4. Storage modulus, G' , as a function of angular frequency of PLA, PBAT, and their blends.

of PBAT increases the elasticity and melt strength of PLA due to the flexible molecular chain of PBAT. Of course, this effect becomes less noticeable as the PLA content decreases.

The same trend is also observed for systems with added carvacrol (see Figure 2). However, in this case, both the pure components and blends exhibit lower viscosity values than their counterparts without carvacrol, along with slightly less pronounced non-Newtonian behavior. This phenomenon can be attributed to the plasticizing effect of carvacrol.^[18,32]

In Figures 4 and 5 the storage modulus (G') of PLA, PBAT, and their blends with and without carvacrol are reported.

It can be observed that the storage modulus exhibits a behavior similar to the complex viscosity situation described above. Specifically, the values of storage modulus do not fall between those of pure PBAT and pure PLA; instead, they show higher values with a decrease in the low-frequency slope, indicating solid-like behavior of the material. Indeed, according to the scientific literature,^[33] the reduction of the slope in the low-frequency ranges correlates with solid-like material behavior.

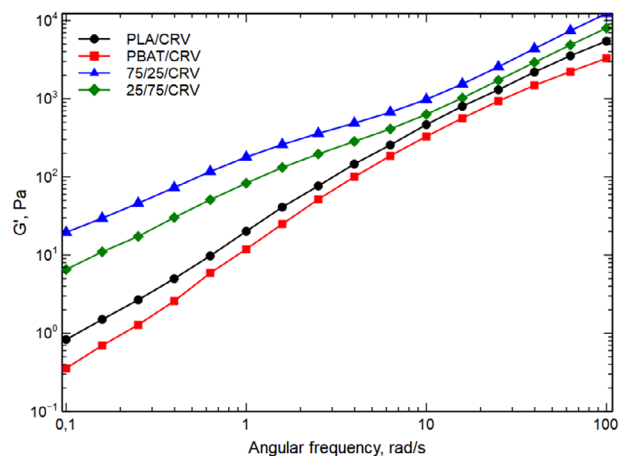


Figure 5. Storage modulus, G' , as a function angular frequency of PLA, PBAT, and their blends with add Carvacrol.

Table 3. Elastic modulus, E, tensile strength, TS, and elongation at break, EB, of all samples investigated.

Sample code	E, MPa	TS, MPa	EB, %
PLA	1592 ± 64 ^a	66 ± 5.0 ^a	6.5 ± 0.9 ^a
PBAT	57 ± 2.6 ^b	27.8 ± 3.1 ^b	800 ± 47 ^b
PLA/CRV	553 ± 48 ^c	12.9 ± 2.7 ^c	304 ± 35 ^c
PBAT/CRV	22 ± 2.4 ^d	11.8 ± 2.4 ^c	1100 ± 69 ^d
75/25	1169 ± 25 ^{a,c}	24.8 ± 3.7 ^b	42.2 ± 9.5 ^e
25/75	130 ± 4.6 ^{b,c}	10.3 ± 0.9 ^{c,d}	238 ± 19 ^c
75/25/CRV	448 ± 39 ^c	8.4 ± 1.5 ^d	329 ± 28 ^c
25/75/CRV	38 ± 4.0 ^d	7.6 ± 1.2 ^d	501 ± 38 ^{b,c}

Different letters in the same column indicate significant differences ($p < 0.05$) according to Tukey's t-tests.

The same trend, albeit weaker, is also observed for samples in the presence of carvacrol. In these samples, the presence of carvacrol leads, in agreement with previous results of complex viscosity, to slightly lower values than the corresponding ones without carvacrol. This behavior is attributable to the plasticizing effect of carvacrol, which reduces the energy required to deform the material, promoting the mobility of the polymer chains and thus reducing their storage modulus and viscosity.

Table 3 summarizes the average values and standard deviations of elastic modulus, E, tensile strength, TS, and elongation at break, EB; while **Figures 6–8** show the trend as a function of PLA content.

PLA is a rigid polymer with an elastic modulus of ≈ 1592 MPa and a tensile strength of 66 MPa, while PBAT is a significantly more flexible material. The elastic modulus of PBAT is ≈ 57 MPa and its elongation at break 800% compared to 6.5% for PLA, see **Table 3**.

As known in the literature and visible in the SEM micrographs reported in the supporting information (Figure S1, Supporting Information), PLA and PBAT are immiscible. Therefore, when mixed, the blend comprises an immiscible biphasic system with PBAT uniformly dispersed as domains within the PLA matrix in 75/25 blends (Figure S1a, Supporting Information) and

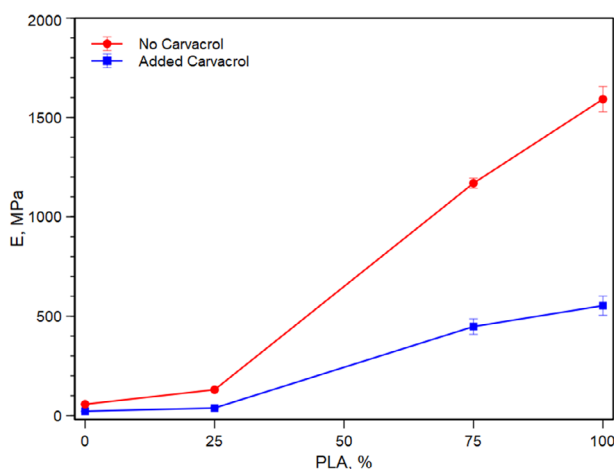


Figure 6. Elastic modulus, E, as a function of % PLA.

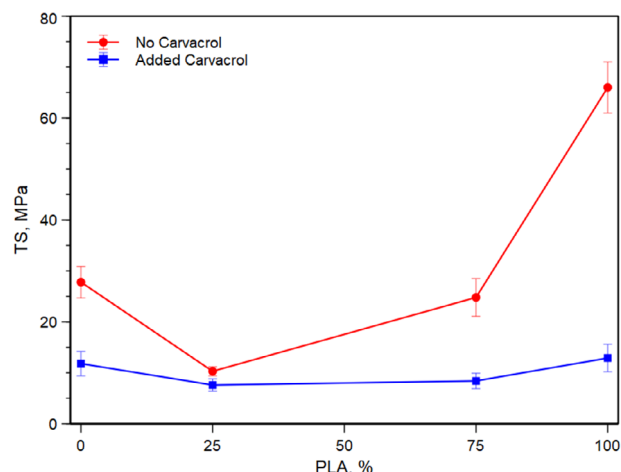


Figure 7. Tensile strength, TS, as a function of % PLA.

PLA in PBAT matrix in 25/75 blends (Figure S1b, Supporting Information).^[34,35] However, the addition of PBAT to the PLA increases the flexibility of the blend, see Figure 6. More in detail, elastic modulus and tensile strength of the blend decreased to $\approx 26\%$ and 60% , but the elongation at break increased to $\approx 550\%$. Conversely, the addition of PLA to PBAT increases the stiffness of the blends. In more detail, the elastic modulus of the blend increases to $\approx 128\%$, but the tensile strength and elongation at break decrease to $\approx 62\%$ and 70% .

The same trend is observed in the specimens with carvacrol, but in this case the lower modulus and tensile strength values and the slight increase elongation at break compared to the corresponding specimens without carvacrol were attributed to the plasticizing act of carvacrol.^[18,31]

The study of surface properties provides important information, in particular when we consider these materials promising for food packaging applications.

In **Figure 9**, images of water droplets on the PLA, PBAT, and their blend with and without carvacrol are shown, while **Table 4** summarizes.

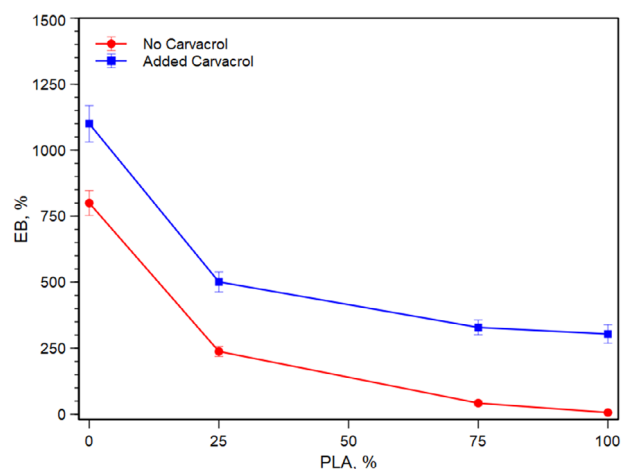


Figure 8. Elongation at break, EB, as a function of % PLA.

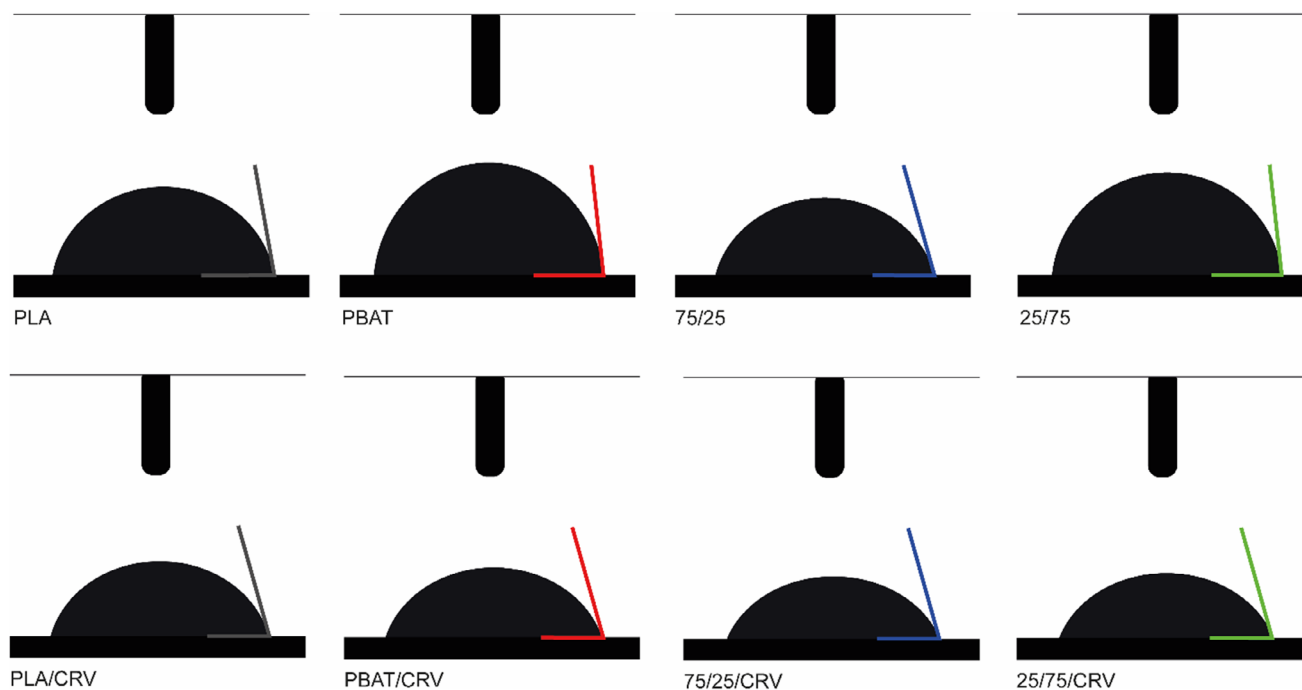


Figure 9. Image droplet water of all samples investigated.

The water contact angle (WCA) values of PLA, PBAT, 75/25, and 25/75 are 77 ± 3.9 ; 87 ± 3.2 ; 71 ± 1.5 ; 85 ± 3.8 , respectively, see Table 4. The contact angle of PLA is more hydrophilic than that of PBAT due to its chemical structure; therefore, the contact angle of 75/25 is reduced compared to that of 25/75 due to the higher content of more hydrophilic PLA in the blend. The addition of CRV results in a decrease in contact angle and therefore an increase in wettability compared to their corresponding ones without carvacrol. This behavior is already found in other systems with essential oils,^[36,37] including carvacrol^[38] and has been attributed to the effect of the oil on surface properties. In particular, the oil may contribute to a smoother surface, potentially influencing the wetting properties of the blend. However, despite this reduction in roughness, the overall low wettability observed in all systems suggests that surface chemistry plays a significant role in determining wetting behavior, as evidenced by the FTIR-ATR spectra shown in the supporting information (Figure S2, Supporting Information). In particular, the slight decrease in the water contact angle can be attributed to the increase in the -OH vibration band at $3200\text{--}3450\text{ cm}^{-1}$ in both PLA/CRV and PBAT/CRV. Furthermore, the presence of the band at 811 cm^{-1} in both the PLA/CRV and PBAT/CRV demonstrates effective mixing with the CRV.^[39]

Table 4. Water contact angle (WCA) value of all samples investigated.

	PLA	PBAT	75/25	25/75
No Carvacrol	77 ± 3.9^a	87 ± 3.2^b	71 ± 1.5^c	$85 \pm 3.8^{a,b}$
Added Carvacrol	69 ± 4.2^a	67 ± 3.9^a	62 ± 2.8^b	63 ± 4.7^b

Different letters in the same row indicate significant differences ($p < 0.05$) according to Tukey's t-tests.

3.1.1. Carvacrol Release Kinetics

In order to study the ability of systems to release carvacrol, controlled release measurements are conducted in water. Figure 10 shows the amount of CVR released by PLA, PBAT, and their blends.

Both PBAT/CRV and the 75/25/CRV blend show a burst release in the first hours of investigation (see box Figure 10), followed by a plateau and a terminal tail due to the gradual depletion of carvacrol. It should be noted that the amount of saturation additive in the 75/25/CRV blend differs from that of PBAT/CRV due to the presence of PLA. In fact, both the PLA/CRV and the 25/75/CRV blend show a slight burst type release, but without significant carvacrol depletion compared to PBAT/CRV. This is due to the fact that PLA releases less carvacrol than other polymers due to its higher glass transition temperature. This means that carvacrol remains trapped in the PLA matrix for longer, reducing its release into the environment and achieving a longer lasting antibacterial effect. Therefore, by modifying the composition of the polymers used, it is possible to control the rate and extent of carvacrol release over time. This ability to adjust the release of the compound offers a potential advantage in the field of formulating controlled-release materials, as it allows the application to be tailored to specific needs.

3.2. Antibacterial Properties

The inhibitory properties of the biodegradable polymers developed in this study are evaluated in vitro against two pathogenic bacterial species, including *L. monocytogenes* among Gram-positive and *S. Enteritidis* among Gram-negative. These bacteria are the main pathogenic agents responsible for bacterial infec-

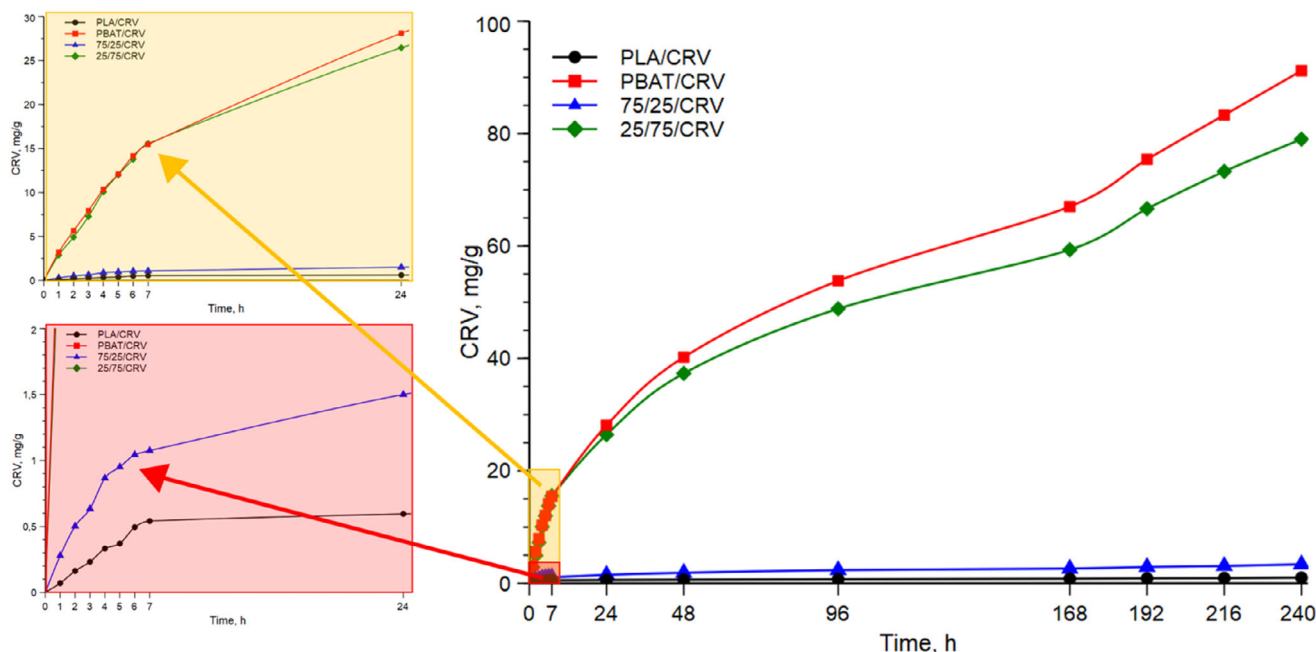


Figure 10. Cumulative Carvacrol release of PLA/CRV, PBAT/CRV and their blends.

tions of food origin^[40] and are generally used to monitor of the microbiological food safety criteria.^[41] The approach followed in this study to evaluate the antibacterial activity of the polymers includes the application of a combined microbiological strategy based on the disc diffusion and the plate counts method. For both assays, pure PLA and PBAT did not reveal any antibacterial activity against the two pathogenic bacteria used as indicators microorganisms; this result confirms what is previously reported in other works.^[42,43] The disc diffusion method showed that the only active polymers were PBAT/CRV and 25/75/CRV blend, which are able to inhibit *L. monocytogenes* and *S. Enteritidis* (Table 5). The inability of PLA/CRV and 75/25/CRV to inhibit the growth of both pathogenic bacteria is imputable to the lower release of CRV compared to the PBAT/CRV and 25/75/CRV blends.

Although the diffusion assay showed a low antibacterial activity, the plate count method clearly evidences that all materials containing CRV are able to exert an antibacterial activity against

the two indicator strains during the entire period of observation (Figure 11a,b).

In particular, PLA/CRV and 75/25/CRV exhibit a bacteriostatic behavior, while PBAT/CRV and 25/75/CRV a bactericidal mode of action. These differences registered among both assays are mainly imputable to the larger material samples, higher diffusion of the active agents and higher contact time in the liquid media in comparison with the solid media.^[44] Only PBAT/CRV and 25/75/CRV cause a decrease of *L. monocytogenes* below the detection limit ($<1 \text{ Log CFU mL}^{-1}$) (Figure 11a) and reduced *S. Enteritidis* of 1 Log cycle (Figure 11b). Scaffaro et al.^[45] observe similar trends in other types of CRV-activated packaging systems, which can be attributed to the higher sensitivity of Gram-positive bacteria to CRV than the Gram-negative bacteria.^[46] As a matter of fact, although CRV is hydrophobic and contains a free hydroxyl group and delocalized electrons able to destroy bacterial cytoplasmic membranes^[47] the presence of a lipopolysaccharide covering layer in the external membrane of Gram-negative bacteria, reduces their permeability to active compounds.^[48]

Table 5. Inhibitory activity of PLA, PBAT, and their blends in solid media.

Samples	Inhibition [mm]	
	<i>Listeria monocytogenes</i>	<i>Salmonella Enteritidis</i>
PLA	–	–
PLA/CRV	–	–
PBAT	–	–
PBAT/CRV	14.0 ± 0.1 ^a	14.0 ± 0.1 ^a
75/25/CRV	–	–
25/75/CRV	13.0 ± 0.1 ^b	10.0 ± 0.0 ^b

Symbols: – no inhibition found; Different letters in the same column indicate significant differences ($p < 0.05$) according to Tukey's t-tests.

4. Conclusion

In this study, carvacrol was incorporated by melt compound into a biodegradable blend commonly used for packaging applications. The effect of matrix composition on rheological, mechanical, and wetting behavior, as well as release kinetics and antibacterial activity against two pathogenic bacteria such as *L. monocytogenes* and *S. Enteritidis* was studied. The rheological analysis confirmed a plasticizing effect of carvacrol, with the biphasic morphology influencing the viscoelastic response. PBAT's flexible molecular structure induced increased elasticity, affecting viscosity and storage modulus. Mechanical properties indicated stronger plasticization effects in the PLA phase. Additionally, the presence of carvacrol led to increased wettability.

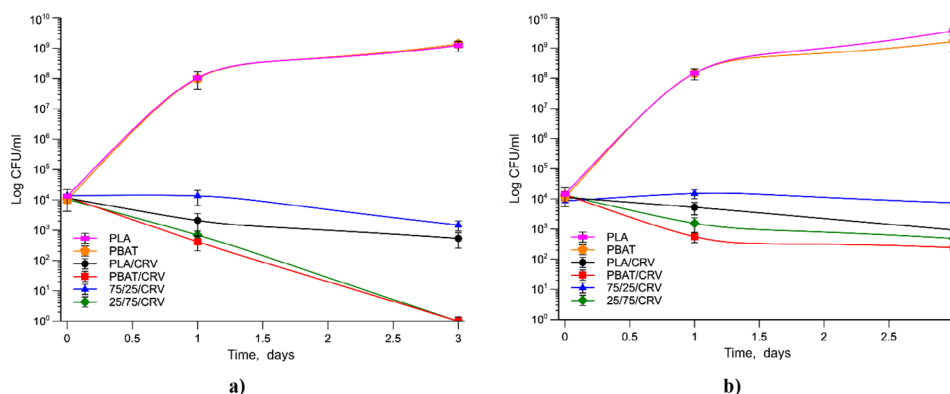


Figure 11. Inhibitory activity of PLA, PBAT and their blends in liquid media a), *Listeria monocytogenes*; b), *Salmonella Enteritidis*.

In vitro evaluation of antibacterial activity showed that the polymers with higher PBAT content and containing CRV inhibited the growth of *Listeria monocytogenes* to undetectable levels ($<1 \text{ Log CFU mL}^{-1}$). Overall, modifying polymer composition enables control over physical properties and the release profile of carvacrol. This offers potential advantages for industrial packaging, allowing the development of materials with controlled release tailored to specific applications.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

L.B. performed conceptualization, investigation, methodology, supervision, wrote the original draft preparation, wrote reviewed and edited the final manuscript. M.C.M. performed data curation, visualization, supervision, wrote reviewed and edited the final manuscript. V.T. performed investigation, data curation, visualization, wrote the original draft preparation, wrote reviewed and edited the final manuscript. S.R. performed investigation. G.G. performed investigation, data curation. R.G. investigation, data curation, wrote the original draft preparation, wrote reviewed and edited the final manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

antibacterial activity, antimicrobial, biopolymer, food packaging, polymer blends, sustainability

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