ORIGINAL ARTICLE

Preparation and characterization of isotactic polypropylene/zinc oxide microcomposites with antibacterial activity

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In this study, we investigated the influence of ZnO particles obtained by spray pyrolysis with submicron dimensions on the structure, morphology, thermal stability, photodegradation stability, mechanical and antibacterial properties of isotactic polypropylene (iPP)/ZnO composites prepared by melt mixing. The results of the morphological analyses indicate that, despite the surface polarity mismatch between iPP and ZnO, the extrusion process and the unique characteristics of the utilized particles allow a composite with a fair distribution of particles to be obtained, although some agglomeration phenomena can occur, which primarily depends on the composition of the composite. The addition of ZnO particles imparts significant improvements on the photodegradation resistance of iPP to ultraviolet irradiation, which confirms that ZnO particles act as screens for this type of radiation. The thermal stability of the iPP/ZnO composites is improved with respect to that of neat iPP and increases with the content of ZnO. The iPP/ZnO composites exhibit significant antibacterial activity against *Escherichia coli*. This activity is dependent on exposure time and composition.

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INTRODUCTION

The interest in polymer materials with enhanced properties that exhibit antimicrobial activity is continuously increasing because of the growing demand for healthy living. The potential fields of application for these materials include, for instance, textiles,^{1,2} food packaging³ or medical devices to prevent infection.⁴ The use of inorganic antibacterial nano- and micro-particles has several advantages over organic agents,^{5,6} including thermal resistance, chemical stability, safety and a longer active period.^{3,7,8} Silver, gold and zinc nanoparticles are the most studied nanoparticles, and silver nanoparticles have already been used in several commercial applications. Nanoscale silver, which possesses high temperature stability and low volatility, is known to be an effective antifungal and antimicrobial material, and it has been reported to be effective against 150 different bacteria.^{9,10} Titanium dioxide (TiO₂), zinc oxide (ZnO), silicon oxide (SiO₂) and magnesium oxide (MgO) have been investigated for their ability to be used as ultraviolet (UV) blockers and photo-catalytic disinfecting agents,¹¹ and they are considered to be safe materials for human beings and animals.¹² More recently, the antimicrobial properties of nanoscale ZnO and MgO have been discovered. Compared with nanosilver, the

nanoparticles of ZnO and MgO are expected to provide more affordable and safe solutions in the future. Nanomaterials containing a nano-ZnO-based photocatalyst, which has been reported to sterilize indoor lighting, have been recently introduced. It has been reported that ZnO exhibits antibacterial activity that increases with decreasing particle size.¹³ This activity does not require the presence of UV light (unlike TiO₂), but it is stimulated by visible light.¹⁴ In particular, the use of ZnO has been viewed as a viable solution for stopping infectious diseases because of its antimicrobial properties.¹⁵ The intrinsic properties of a metal nanoparticle are primarily determined by its size, shape, composition, crystallinity and morphology.¹⁶ ZnO particles have been incorporated into a number of different polymers, including low density polyethylene (LDPE),^{17,18} isotactic polypropylene (iPP),^{19–23} polyvinyl acetate (PVA),²⁴ polyamide (PA)²⁵ and cotton woven fabric,²⁶ for more than antimicrobial purposes.

For example, in Low Density Polyethylene/ZnO composites prepared using the melt-mixing process, ZnO powders (sizes of 200 and 2 μm) were used as reinforcing particles for improving the dielectric and conductivity properties of the composite.¹⁷ Polyvinyl acetate/ZnO nanocomposites have potential applications as a photoanode in

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high-efficiency dye-sensitized solar cells, light-emitting diodes, lasers, field-emission devices and chemical sensors.²⁰ Nano-ZnO coated cotton fabric²⁴ has been observed to exhibit antimicrobial properties against *Staphylococcus aureus* and *E. coli* in both qualitative and quantitative tests. Antimicrobial activity has also been observed for Low Density Polyethylene and PA6/ZnO composites.¹⁸

iPP is one of the most important commercial polymers due to its low price and an attractive combination of good processability, mechanical properties and chemical resistance.^{27,28} Furthermore, iPP films are used in packaging applications because of their strength, transparency brilliance, low specific weight and high chemical inertness.^{29,30} Compounding iPP with inorganic particles is an effective method for improving the properties of iPP.^{31–33} Zhao and Li¹⁹ investigated the use of ZnO as an ultraviolet absorber in iPP. Huang *et al.*²⁰ added ZnO nanopowder through microinjection molding to investigate the mechanical properties of iPP. Lepot *et al.*²¹ have investigated the effects of the concentration and shape of ZnO on the processing and properties of biaxially oriented polypropylene-ZnO nanocomposites. Tang *et al.*²³ reported that ZnO is a good nucleating agent and that ZnO nanoparticles coated with organic nucleating agents affect the morphology and crystallization of iPP. In this article, iPP/ZnO composites were prepared using the melt-mixing technique. ZnO particles with submicron dimensions have been obtained at the pilot scale using spray pyrolysis.³⁴ This technique offers specific advantages compared with other material processing techniques, such as gas-to-particle conversion processes and liquid or solid-state processing followed by milling. These advantages are a higher purity of the produced powders, a better uniformity in the chemical composition, a narrower size distribution, a better regularity in shape (spherical) and the synthesis of multicomponent materials. Another significant advantage to be noted is the relative simplicity of the process, which could allow scale-up, such as that recently performed by the PYLOTE company.^{35,36}

The primary objective of this study is to investigate the influence of ZnO microparticles on the morphology, photodegradation stability and antibacterial activity of iPP/ZnO composites. The analysis of the mechanical properties completes the characterization of these materials. This paper is the first of a series that aims to exploit the potential of iPP/ZnO-based composites. In the following paper, the influence of compatibilizing agents based on polypropylene grafted with maleic anhydride and of the processing conditions to improve the particles dispersion will be reported.

EXPERIMENTAL PROCEDURE

Materials and sample preparation

The zinc oxide particles were produced using a preindustrial scale spray pyrolysis platform. During the production process, droplets of a precursor solution (zinc nitrate) were dried and decomposed into the required compound. The presence of an additional soluble flux in the precursor solution permitted the formation of agglomerate-free particles after washing the product. The production rate was $\sim 100 \text{ g h}^{-1}$ of powders.

Before mixing, ZnO was dried in an oven at 100°C for 3 h. Pure iPP (Moplen X30S), which was kindly supplied by Basell (Ferrara, Italy), has a melt flow index $= 9 \text{ dg min}^{-1}$ (measured at 230°C), a $M_w = 3.5 \times 10^5$ and a $M_n = 4.7 \times 10^4$.

iPP and ZnO were compounded at the desired compositions in a 25-mm twin-screw extruder ($L/D = 56$). The temperature setting of the extruder from the hopper to the die was $180/200/200/190/180^\circ\text{C}$, and the screw speed was 25 r.p.m. The mixing ratios of iPP/ZnO (wt/wt) were 100/0, 98/2 and 95/5.

Films of iPP and iPP/ZnO were obtained by compression molding in a press at 210°C and 100 bar. The mold had a rectangular shape with dimensions of $100 \times 90 \text{ mm}$ and a thickness of $130 \mu\text{m}$.

Characterization

Morphological characterization (scanning electron microscopy (SEM)) was performed on pellets obtained from the extruder, whereas the mechanical properties, barrier properties, UV ageing and structural analysis (WAXS) were performed on compression molded films.

Scanning electron microscopy. The surface analysis was performed using a SEM, PHILIPS model XL20, on particles of the powders and on cryogenically fractured surfaces of composites. Before the observation, samples were coated with a Au/Pd alloy using an E5 150 SEM coating unit.

Thermogravimetric Analysis. The thermal behavior of the blends was examined by thermogravimetric analysis (TGA) using a Perkin Elmer-Pyris Diamond apparatus with a heating rate of $10^\circ\text{C min}^{-1}$ in air. Two measurements were performed for each sample.

Mechanical tests. Dumbbell-shaped specimens were cut from the compression molded films and used for the tensile measurements. Stress-strain curves were obtained using an Instron machine (Model 4505) at room temperature (25°C) at a crosshead speed of 5 mm min^{-1} . Ten tests were performed for each composition.

Photo-oxidation tests. The UV-irradiation treatments for the unfilled iPP and iPP/ZnO composite films were performed using a UV-accelerated weathering tester (Sunrise, Angelantoni Industrie ACS, Perugia, Italy, UVA 360 nm), with a light intensity of 20 W m^{-2} . Both surfaces of the films were subjected to the UV irradiation for 600 h at a temperature of 40°C . During the UV-irradiation treatment, the samples were subjected to Fourier transform infrared (FTIR) analysis. The molecular degradation of the samples was characterized based on the carbonyl index, which was calculated using Equation (1):

$$\text{Carbonyl index} = A_c/A_r \quad (1)$$

where A_c is the area of the carbonyl absorption band (in the range of $1670\text{--}1780 \text{ cm}^{-1}$) and A_r is the area of the reference band (in the range from $870\text{--}820 \text{ cm}^{-1}$). The carbonyl band reflects several degradation products. The reference band is not affected by photo-oxidation nor by varying crystallinity.³⁷

Wide-Angle X-ray Diffraction. Wide-angle X-ray diffraction (WAXD) measurements were conducted using a Philips XPW diffractometer (Philips Analytical, Almelo, The Netherlands) with $\text{Cu K}\alpha$ radiation ($1.542 \text{ \AA}$) filtered by nickel. The scanning rate was $0.02^\circ\text{C min}^{-1}$, and the scanning angle was from 5 to 45° (for ZnO, from 10 to 60°). The ratio of the area under the crystalline peaks and the total area multiplied by 100 was taken as the crystalline percentage degree. Measurements were performed on compression molded films and on aged films after 300 and 600 h of exposure to UV radiation.

Antibacterial evaluation. The antimicrobial activity of the iPP/ZnO composites was evaluated using *E. coli* DSM 498^T (DSMZ, Braunschweig, Germany) as test microorganisms. The evaluation was performed using the ASTM Standard Test Method E 2149-10 preparation of the bacterial inoculum required us to grow a fresh 18-h shake culture of *E. coli* DSM 498 in a sterile nutrient broth (LB composition for 1 l: 10 g of triptone, 5 g of yeast extract and 10 g of sodium chloride). The colonies were maintained according to good microbiological practice and examined for purity by creating a streak plate. The bacterial inoculum was diluted using a sterile buffer solution (composition for one liter: 0.150 g of potassium chloride, 2.25 g of sodium chloride, 0.05 g of sodium bicarbonate, 0.12 g of calcium chloride $6 \text{ H}_2\text{O}$ and a pH of 7) until the solution reached an absorbance of 0.3 ± 0.01 at 600 nm, as measured spectrophotometrically. This solution, which had a concentration of $1.5\text{--}3 \times 10^8$ colony forming units (CFUs) ml^{-1} , was diluted with the buffer solution to obtain a final concentration of $1.5\text{--}3 \times 10^6$ CFUs ml^{-1} . This solution was the working bacterial dilution.

The experiments were performed in 50-ml sterilized flasks. One gram of the film was maintained in contact with 10 ml of the working bacterial dilution. After 2 min, 100 μl of the working bacterial dilution was transferred to a test tube, which was followed by serial dilution and plating out on Petri dishes ($10 \text{ mm} \times 90 \text{ mm}$) in which the culture media was previously poured. The petri dishes were incubated at 35°C for 24 h. These dishes represented the T_0

contact time. The flasks were then placed on a wrist-action shaker for 1 h (T_1), 24 h (T_2) and 48 h (T_3). The bacterial concentration in the solutions at these time points was evaluated by again performing serial dilutions and standard plate counting techniques. Three experiments were performed for each composition. The number of colonies in the petri dish after incubation was converted into the number of colonies that form a unit per milliliter (CFUs ml^{-1}) of buffer solution in the flask. The percentage reduction was calculated using the following formula.

$$\text{Reduction } \% (\text{CFU } \text{ml}^{-1}) = (B - A/B) \times 100 \quad (2)$$

where $A = \text{CFUs } \text{ml}^{-1}$ for the flask containing the sample after the specific contact time and $B = \text{CFUs } \text{ml}^{-1}$ at T_0 .

RESULTS AND DISCUSSION

Structure and morphology

The SEM micrograph clearly reveals that the ZnO powders obtained by spray pyrolysis (Figure 1a) are composed of spherical particles that have an average diameter of 490 nm (d_{50}) and a BET surface area equal to $13.5 \text{ m}^2 \text{ g}^{-1}$. The X-ray diffraction pattern of the particles (Figure 1b) presents the characteristic peaks of ZnO with no

unidentified peaks, which indicates that the produced particles have a high purity. The size of a single zinc-oxide crystal, which was calculated by applying the Scherrer formula³⁸ to the reflection at 47.7° for the 102 plane, is 20–25 nm.

Figure 2a presents the SEM image of the fractured surface of the 98/2 wt/wt iPP/ZnO composite. ZnO is homogeneously dispersed in the iPP matrix with few agglomeration phenomena present. Moreover, a good adhesion between the phases is also evidenced by the complete absence of voids.

These results indicate that, despite the surface polarity mismatch between iPP and ZnO, the extrusion process together with the novel particles utilized allows a composite to be obtained that has a fair distribution of particles and good adhesion between the phases.

The same features were observed for the 95/5 iPP/ZnO composite (Figure 2b). However, some agglomerates that were dimensionally larger than those observed for the 98/2 iPP/ZnO composite, are present in this blend, as shown in Figure 3. This figure shows one of these agglomerates and its interfacial adhesion with iPP.

Thermodegradation analysis

TGA measurements were performed in an air atmosphere at a heating rate of $10^\circ \text{C min}^{-1}$. The thermogravimetric curves of all the samples are shown in Figure 4. From these curves, two parameters were extracted and are reported in Table 1, which include $T_{5\%}$ and T_{max} ; the first parameter, $T_{5\%}$, is the temperature on the curve when the sample has lost 5% of its weight, and T_{max} is the temperature at the inflection point of the curve (detected at the maximum of the peak of the first derivative of the curve), which corresponds to the maximum rate of the degradation of the sample.

The thermogravimetric curves indicate that the thermal decomposition is a one-step process for all the samples. The $T_{5\%}$ values for the two composites are slightly less than that of iPP. This result indicates that the degradation of the composite begins before the degradation of iPP, which is most likely due to the catalytic effect of the metal oxide on the degradation of iPP and is consistent with results reported in the literature.³⁹

In contrast, the T_{max} of the composites is greater (352 and 382°C , respectively) than that of plain iPP (335°C) and increases with the composition, which suggests that the iPP/ZnO composites have a greater thermal stability; this enhanced thermal stability is also evident from the shift of the curves at higher T , as shown in Figure 4. This behavior could be explained by hypothesizing that nano- and submicron-ZnO particles that are well dispersed in the iPP matrix (see morphological section) create a barrier labyrinth that slows the diffusion of the degradation products from the bulk of the polymer to the surface of the sample.⁴⁰

Photodegradation analysis

It is well-known that the degradation of iPP can be induced by irradiation within the wavelength range of 310–360 nm⁴¹ and that it produces hydroperoxides and carbonyl species, such as ketones, esters and acids.^{42,43} By using FTIR spectroscopy, the degradation products induce the evolution of absorption peaks in the wavenumber ranges of 3200–3600 and $1600\text{--}1800 \text{ cm}^{-1}$.

In Figure 5, the evolutions of the FTIR spectra in the wavenumber range of $1670\text{--}1780 \text{ cm}^{-1}$ are examined for samples irradiated with UV for 0, 300 and 600 h of exposure. Comparing the FTIR spectra for iPP, the evolution of the absorption peaks within the carbonyl region is very dramatic, whereas for the composites, these peaks increase slowly. The evolution of the characteristic peaks for the photodegradation of iPP has been investigated in detail.⁴⁴ At the beginning of

Figure 1 SEM micrograph at a magnification of $\times 10\,000$ (a) and wide-angle diffraction pattern (b) of ZnO particles obtained by spray pyrolysis.

Figure 2 SEM micrographs of the fractured surface of the 98/2 iPP/ZnO (a) and 95/5 iPP/ZnO (b) composites at a magnification of $\times 5000$.

Figure 3 SEM micrographs of the fractured surface of the 95/5 iPP/ZnO composite at a magnification of $\times 20\,000$.

Figure 4 TGA curves for iPP and iPP/ZnO composites obtained under air.

Table 1 $T_{5\%}$ ($^{\circ}\text{C}$) and T_{max} ($^{\circ}\text{C}$) measured by TGA

	$T_{5\%}$ ($^{\circ}\text{C}$)	T_{max} ($^{\circ}\text{C}$)
iPP	261	335
iPP/ZnO 2%	255	352
iPP/ZnO 5%	257	382

Abbreviations: iPP, isotactic polypropylene; TGA, thermogravimetric analysis.

the UV exposure period, carboxylic acid was initially formed, and with exposure periods greater than 60 h, the formation of ketones and lactones occurs.⁴⁵

For a quantitative analysis of the extent of the photodegradation, the carbonyl indices for iPP and iPP/ZnO composites as a function of time were calculated (Equation (1)), which are presented in Figure 6. This graph reveals that the carbonyl indices for the composites are always less than that of iPP. It can be concluded that ZnO particles have an important role in stabilizing the iPP molecules and delay the photodegradation process by functioning as screens that absorb the UV radiation and consequently reduce the UV intensity that results in the oxidation of the iPP chains. However, because no new peaks were observed during UV irradiation in the iPP/ZnO composites when compared with neat iPP, the photodegradation mechanisms for all the systems should be identical. Similar outstanding photo-stabilization effects have been reported for iPP/ZnO,⁴⁶ linear low density polyethylene (LLDPE)/ZnO⁴⁷ and iPP/Montmorillonite (MMT) nanocomposites.^{42,48}

The structures of the samples before and after irradiation were investigated using WAXD. The WAXD patterns (not reported) reveal that iPP and the iPP/ZnO composites always crystallize in the monoclinic α -form. These observations are in contrast with other studies of iPP/ZnO nanocomposites in which it was shown that both nanoscale^{19,23} and micron²³ ZnO functions as a nucleating agent for the β -form.

In Table 2, the crystallinity index, which was measured from the X-ray diffraction patterns, is reported for all of the systems at 0, 300 and 600 h of UV exposure. For all the samples at 0 h, the crystallinity index referring to the iPP phase does not vary with the content of ZnO. For iPP, after 300 h of UV exposure, the crystallinity index increases and then it remains constant until the end of the exposure. For the composites after 300 h of exposure, the crystallinity index does not significantly change, whereas it increases and becomes similar to that of iPP after 600 h of UV exposure.

When exposed to a source of chemical degradation, the morphology of semi-crystalline polymers may be modified,⁴⁹ and in some

cases, disruption of the crystalline order occurs as detected by a reduction in the fractional crystallinity.⁵⁰ In other cases, however, the crystallinity has been reported to increase during exposure.⁵¹ It is generally accepted that the latter occurs because chemical degradation causes scission of molecular chains with the consequent release of

segments of entangled and tie chain molecules in the amorphous region that were unable to crystallize during the original solidification process. These freed segments can subsequently rearrange into a crystalline phase, provided they have sufficient mobility. This process is known as chemi-crystallization.⁵² The results obtained by WAXD clearly indicate, according to the FTIR results, that ZnO delays the chemi-crystallization of iPP.

Figure 5 FTIR spectra for iPP (a), 98/2 iPP/ZnO (b) and 95/5 iPP/ZnO (c) at different UV exposure times.

Mechanical Properties

The tensile parameters for the composites, such as the Young's modulus, the stress and strain at the yield point and those at the break point, are presented in Table 3. iPP displays a ductile behavior, with a yield point, cold-drawing region and fiber formation region; the elongation and the stress at break were observed at almost 900% and at ~ 30 MPa, respectively. The two composites still present a ductile behavior, but the rupture occurs during the fiber formation region at values that depend on the content of ZnO. In fact, for the 2 and 5% filled systems, the elongation at break decreases to 640% and 500%, and the stress at break decreases to 20 and 16 MPa, respectively.

Figure 6 Evolution of the carbonyl index in the infrared spectra of iPP and the iPP/ZnO composites as a function of aging.

Table 2 WAXD crystallinity index calculated at 0, 300 and 600h of UV exposure

	X_c (0h) (%)	X_c (300h) (%)	X_c (600h) (%)
iPP	46 ± 2	55 ± 2	54 ± 2
iPP/ZnO 2%	45 ± 2	49 ± 2	56 ± 2
iPP/ZnO 5%	47 ± 2	48 ± 2	55 ± 2

Abbreviations: UV, ultraviolet; WAXD, wide-angle X-ray diffraction.

Table 3 Stress-strain parameters of iPP and the iPP/ZnO composites

	E (MPa)	σ_y (MPa)	ε_y (%)	σ_b (MPa)	ε_b (%)
iPP	1350 ± 100	19 ± 3	7 ± 2	30 ± 3	890 ± 65
iPP/ZnO 2%	1360 ± 150	19 ± 2	6 ± 1	20 ± 4	640 ± 120
iPP/ZnO 5%	1430 ± 166	19 ± 2	6 ± 1	16 ± 4	500 ± 120

Abbreviation: iPP, isotactic polypropylene.

The addition of 2% of ZnO does not affect the Young's modulus, and an increase of $\sim 6\%$ is observed only for the 5% of ZnO sample. Note that the addition of the ZnO induces an increase in the errors on the measurements of the Young's modulus and elongation at break, which indicates instability during the deformation when the samples are submitted to tensile tests. No variation in the yield parameters is observed.

The results reported here do not show the so-claimed increase in mechanical properties that are usually observed in nanocomposites. This result should be because particles utilized have submicrometric dimensions; moreover, the presence of agglomerates, which were shown in the SEM micrographs, could serve as defect points that facilitate failure of the polymer. However, the composites still exhibit ductile behavior that differs from classical microcomposites. Studies are in progress for determining a compatibilizing agent between iPP and ZnO that is capable of increasing the interconnection between the

phases and to obtain better mechanical properties, and this will be the subject of a forthcoming paper.

Antibacterial activity

In Figure 7, the antimicrobial effect against *E. coli* is presented as a function of time for the different composites. Without ZnO particles, the reference concentration of the micro-organism is measured to be $\sim 2 \times 10^6$. After 1 h, no change in the concentration was observed for any of the samples. By increasing the time, a decrease in the *E. coli* concentration is observed for the composites. The effect is more evident for the 95/5 iPP/ZnO composite. A visual method for observing the biocide effect of the ZnO particles is shown in Figure 8. In Figure 8a, the bacterial growth of *E. coli* after 48 h of contact between the solution and neat iPP is obvious on the petri dish. In Figure 8b, it is evident that at the same contact time, no bacterial growth was observed for the 95/5 iPP/ZnO composite.

The quantitative bacterial reduction was examined by determining the percentage reduction (Equation 2), and the results are shown in Table 4. Neat iPP exhibits no bactericidal activity, and R was observed to be zero at any time. The 95/5 iPP/ZnO composite exhibited maximum reduction after 48 h with a percentage of 99.9%.

Although the antibacterial activity of ZnO is well-known, the mechanisms responsible for the antibacterial activity of metal oxide nanostructures are not fully understood; the proposed mechanisms

Figure 7 Effect of time and filler content in the iPP/ZnO composites on the antibacterial activity.

Table 4 Percent reduction of *E. coli* at different times of contact with films of iPP and the iPP composites

	Percent reduction ($t = 1\text{ h}$)	Percent reduction ($t = 24\text{ h}$)	Percent reduction ($t = 48\text{ h}$)
iPP	0	0	0
iPP/ZnO 2	0	55.1	90.2
iPP/ZnO 5	0	85.3	99.9

Abbreviation: iPP, isotactic polypropylene.

Figure 8 (a) Control plate without ZnO nanoparticles for measuring the growth of *E. coli* after 48 h, (b) Antibacterial effect of ZnO nanoparticles in the 95/5 iPP/ZnO composite after 48 h.

imply that active oxygen species are generated by ZnO particles, although there is no direct evidence from the results reported in the literature.⁵³

It has already been demonstrated that both nano-sized and micron-sized ZnO suspensions are active in inhibiting the growth of bacteria and that the nano-sized ZnO suspension has greater activity than the micron-sized ZnO suspension.⁵⁴ These results are consistent with the results reported in this paper, which also indicate that the submicron ZnO obtained by spray pyrolysis exhibits a substantial bactericidal effect that is similar to that obtained for particles with nanoscale dimensions.

CONCLUSIONS

In this paper, the influence of ZnO particles obtained by spray pyrolysis with submicron dimensions on the structure, morphology, photodegradation stability and thermal, mechanical, barrier and antibacterial properties of iPP/ZnO composites prepared by melt mixing has been investigated. It was observed that despite the surface polarity mismatch between iPP and ZnO, the extrusion process together with the particular particles utilized allows a composite with fair distribution of particles to be obtained.

The principal achievements of the novel composites with respect to pure iPP are (i) the antibacterial activity against *E. coli*; for the 95/5 iPP/ZnO composite, the percentage of bacteria reduced after 48 h is of 99.9% and (ii) the significant improvements in the photodegradation resistance of iPP to UV irradiation.

Several other interesting results were obtained, including:

- (1) The thermal stability of iPP/ZnO composites is improved with respect to neat iPP and increases with the ZnO content;
- (2) The iPP/ZnO composites remain ductile with an elongation at break value of 500%, even with the incorporation of 5% of ZnO. The addition of 2% of ZnO does not affect the modulus, whereas with the addition of 5% of ZnO, an increase of 6% was observed. No variation in the yield parameters was observed.

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