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RECYCLING OF PERSONAL PROTECTIVE EQUIPMENT: SANITISATION, DEGRADATION AND POLYMER BLEND FORMULATIONS

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Keywords: recycling, personal protective equipment, polypropylene, sanitisation, blends

ABSTRACT

Despite being one of the most widely used polymers, polypropylene (PP) has a recycling rate of just 5%, mainly due to difficulties in separating it from other polyolefins and contained additives, as well as its tendency to quickly degrade during reprocessing and use. However, face masks, composed of pure PP without additives and designed for short-term use, offer a unique recycling opportunity.
This research explores the recycling potential of PP from disposable face masks, focusing on how different sanitisation methods— ultrasounds and aqueous hypochlorous acid (HClO) solution— impact the material's properties. The research evaluates the extrusion reprocessing of both sanitised and unsanitised PP, in its pure form and when blended with virgin PP at different ratios (90/10, 70/30, 50/50 by weight), for potential applications such as cast film extrusion and additive manufacturing. Results highlight that different PP grades are used in the mask's layers for specific filtrations roles. However, the recycling process considered in this study did not separate these layers, simplifying industrial applicability. After sanitisation and extrusion processes, no evidence of chemical oxidation was found, but rheological analyses revealed polymer chain breakdown and reduced molecular weight. Blending the recycled polymer with virgin PP, modified rheological, thermal and mechanical properties with variations depending on the blend composition.
Incorporating virgin polypropylene to enhance the performance of the recyclate demonstrates the feasibility of recovering a valuable material that, properly sanitised, retains properties suitable for industrial processes such as cast film extrusion and additive manufacturing. This approach underscores the potential of recycling strategies to convert discarded surgical masks from waste into valuable and make a significant contribution to the circular economy model.

1. INTRODUCTION

The EU's Green Deal and Italy's National Recovery Plan highlight the urgent need for a transition to a circular economy, aiming to conserve resources by reducing the demand for raw materials and energy, minimising waste by keeping resources in use and avoiding disposal challenges. This model stands in contrast to the traditional linear economy, which operates on a "take, make, use, dispose" principle, responsible for depleting finite resources and harming the environment through waste accumulation [1–4].
Plastics pose a significant challenge in the linear economy because of their extensive use and lasting environmental effects since poor solid waste management and improper disposal have resulted in

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their status as pervasive contaminants [5]. It has been forecasted that plastic waste will double by 2030, despite various initiatives undertaken by governments around the globe to minimise consumption and littering of single-use items [6,7]. Globally, approximately 380 million tons of plastics are produced annually, with polyolefins making up over 60% of municipal solid waste. However, less than 20% of these plastics are recycled after use, while the majority are either incinerated or dumped in landfills and oceans, leading to a loss of valuable resources [8].

The issue became even more critical during the COVID-19 pandemic, as the sudden surge in demand for disposable plastics placed additional strain on waste management systems [9,10]. In particular, the use of personal protective equipment (PPE), including face masks, face shields, gloves, isolation gowns, shoe covers and hair nets, significantly increased as an effective measure to prevent the transmission of the virus [11,12]. During the emergency, Italy's monthly demand reached 1 billion masks and 0.5 billion gloves [13,14], generating an urgent need for the Italian factories to convert their production to meet the demands of the new crisis situation.

Polyolefins account for about two-thirds of the global plastic consumption, with polypropylene (PP) being the most widely used polymer in the EU, with a total amount close to ca. 10 MT and corresponding to a share of ca. 20% [15]. The appealability of PP lies in its extreme versatility, making it suitable for numerous applications, such as packaging, toys, car components, tanks and pipes for chemicals, medical vials and even nonwoven fabrics and textiles for PPE [16]. However, it is one of the least recycled plastics, at a rate of ca. 5% of post-consumer recovery, considerably lower than other polymers such as polyethylene terephthalate (21%) and polyethylene (9%) [17]. This fact is primarily due to challenges in separating it from other polyolefins, the presence of additives in PP products, and its susceptibility to rapid thermal and photo-degradation during reprocessing and use [18,19]. However, polypropylene used in disposable face masks presents a unique opportunity for recycling, as it has a naturally short lifespan, thus a reduced degradation, and lacks other polyolefins or additives in its composition.

From this perspective, it is convenient to consider strategies capable of recovering valuable and abundant material that can still be used for other purposes [20]. Indeed, the use of PPEs, a well-consolidated practice in medical, food and electronic sectors even prior to COVID-19, has been strongly amplified by the crisis, leading to the generation of 8.4 million metric tons of plastic waste by August 2021 alone [21]. According to the United Nations Environment Program [22], about 75% of used masks and other pandemic-related waste ended up in landfills or seas, not accounting for the PPE waste that originates from medical, food and electronic sectors, which account for more than MT/month and are either landfilled or incinerated.

PPEs and nonwoven production scrap can be heat-treated at very high temperatures to recover gaseous and liquid fuels and solid particles, called char, or subjected to sanitisation and further reprocessing for materials recovery [23]. Overall, the sanitisation of polymer-based devices and/or personal protection equipment involves processes aimed at reducing or eliminating microbial contamination on the surfaces of the items, and this is obviously of particular importance in industries such as medical devices, food packaging and pharmaceuticals. Some common methods used to sanitise polymers are: *(i)* chemical sanitisation, which consists of the use of chlorine-based compounds, alcohols, quaternary ammonium compounds, etc.; *(ii)* heat treatment, such as autoclaving or other heat sterilisation; *(iii)* ultrasonic treatment, which consists in damaging the microorganisms through the cavitation effect; *(iv)* ultraviolet light treatment, which is highly effective against bacteria and viruses; *(v)* gamma and electron beam irradiation, which consists of damaging microbial DNA; *(vi)* plasma treatment; *(vii)* mechanical cleaning by washing and soaking [24]. The selection of the most appropriate sanitisation method must be approached carefully, considering various factors such as polymer types and properties, conditions and uses, regulatory requirements, etc., to avoid polymer damage and degradation [25]. Particularly for PPEs characterised by short useful life, choosing a sanitisation method that preserves polymer integrity can enhance the material's potential for recycling and reuse, thereby reducing waste and promoting circularity.

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Based on information from the literature, mechanical recycling of polypropylene consists of its reuse through *(i)* reprocessing, *(ii)* blending with virgin polypropylene, *(iii)* adding appropriate stabilisers, reinforcing agents (such as carbon-based fibres, glass fibres, minerals, clays, etc.), dyes, impact modifiers, etc., considering a different type of second-life applications [23,26,27]. However, reprocessed post-consumer PP shows a rapid reduction in performance and properties: PP is generally degraded by β-scission, with random chain scission and radical formation leading to a reduction in the molecular weight and the simultaneous formation of crosslinked structures. Structural variations related to changes in molecular weight, molecular architecture and crystallinity also lead to considerable variations in mechanical and thermo-mechanical behaviour; therefore, the use of additives is almost always necessary. In other cases, blending recycled and virgin PP can maintain the desired properties, particularly when the recycled material has undergone minimal degradation.
This study examines the potential benefits of recycling PP from surgical face masks, narrowing on how sanitisation processes affect the properties of the recycled material. The research explores the mechanical recycling of PP nonwovens through extrusion reprocessing, both in their pure form and when blended with virgin polypropylene, assessing the materials' processability for cast film extrusion and material extrusion-based additive manufacturing. First, face masks were sanitised using two methods: ultrasound (US) treatment and chemical sanitisation with an aqueous hypochlorous acid (HClO) solution. Subsequently, the properties of untreated recycled polypropylene (PPr) and sanitised recyclates (US-PPr and HClO-PPr) were compared with the original material and with one another to evaluate any degradation caused by the extrusion and sanitisation processes. As second step, blends were prepared at three different compositions (50/50, 70/30 and 90/10 wt%) by mixing the recyclates with a virgin polypropylene (PPv) graded for extrusion film. A preliminary rheological characterisation, including melt flow rate (MFR) and flow curve analysis, was performed to assess the processability of materials and their compatibility with conventional manufacturing processes.

2. MATERIALS AND METHODS

2.1 Materials

In this study, Moplen HP515M, graded for film extrusion with a density of 0.90 g/cm^3, was supplied by LyondellBasell and used as virgin polypropylene (PPv). Recycled PP (PPr) was produced by mechanical recycling of new 3-ply surgical face masks (net weight ≈ 4.41 ± 0.05 g).

2.2 Equipment and processes for sanitisation and production

2.2.1 Sanitisation of face masks

Polypropylene obtained by face mask was shredded and then subjected to simulated sanitisation processes by means of an aqueous hypochlorite (HClO) solution and treatment with ultrasounds (US). In the first case, the samples were immersed in 1000 mL of the aqueous hydrogen chloride solution (HClO) under stirring at a concentration of 100 mg/L at 25 °C for 30 minutes [24]. For the US treatment, the shredded masks were subjected to ultrasonic cleaning via the utilisation of an ultrasonic cleaner bath (ARGO LAB DU-32S). This was conducted in a de-ionized aqueous bath at a frequency of 40 kHz, a temperature of 30 °C, and a maximum power of 120 W, for a period of 30 minutes.

2.2.2 Production of recycled PP

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The recycled PP was produced by mechanical recycling of the face masks, that, after the removal of the metallic nose wire and the elastic ear loops, were thermopressed with a Carver laboratory press (T = 200°C, P = 6000 Pa, for 3 minutes), shredded and fed to a Brabender Do-Corder 330 single-screw extruder (D=20 mm; L/D=20). A screw speed of 30 rpm was imposed, and a temperature profile of 165 - 170 - 170 °C was set along the barrel. The extruded strand was air-cooled and then pelletised in a SCHEER SGS 25-E4 lab pelletiser (C. f. SCHEER & CIE, Stuttgart, Germany). The production steps are schematised in Figure 1a.

2.2.3 Preparation of PPv/PPr blends

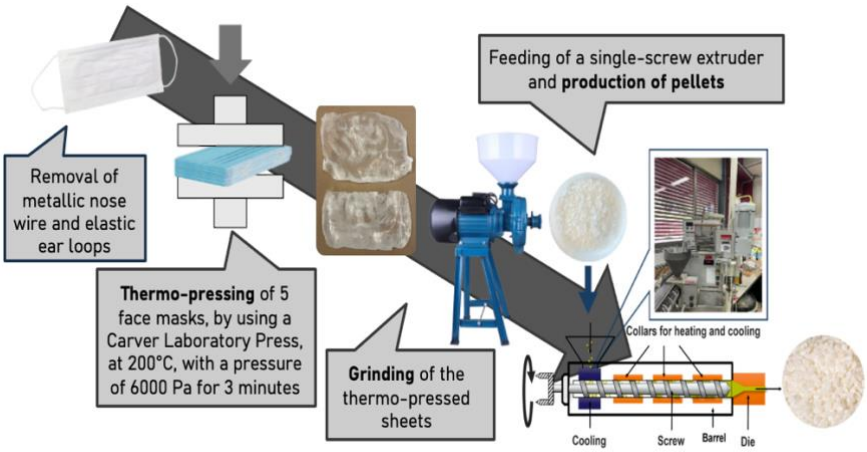
The PPv and PPr pellets at different PPv/PPr ratios (50/50, 70/30, 90/10 by weight) were melted and mixed in a Collin ZK 25-48D co-rotating twin extruder (COLLIN Lab & Pilot Solutions GmbH, Maitenbeth, Germany, D = 25 mm, L/D = 42), at a screw speed of 100 rpm and with a temperature profile of 185 - 185 - 185 - 190 - 190 - 190 - 190 - 185 °C. After air-cooling, the extruded strand was pelletised.
To assess the effect of the sanitisation technique, nine different blends were produced. For each composition, three distinct blends were developed using mechanically recycled PP derived from untreated face masks (PPr), face masks treated with HClO aqueous solution (HClO-PPr), and face masks treated with ultrasounds (US-PPr).
The names and compositions of the produced samples are listed in Table 1.

Table 1 *- Names and composition of PPv/PPr blends produced*

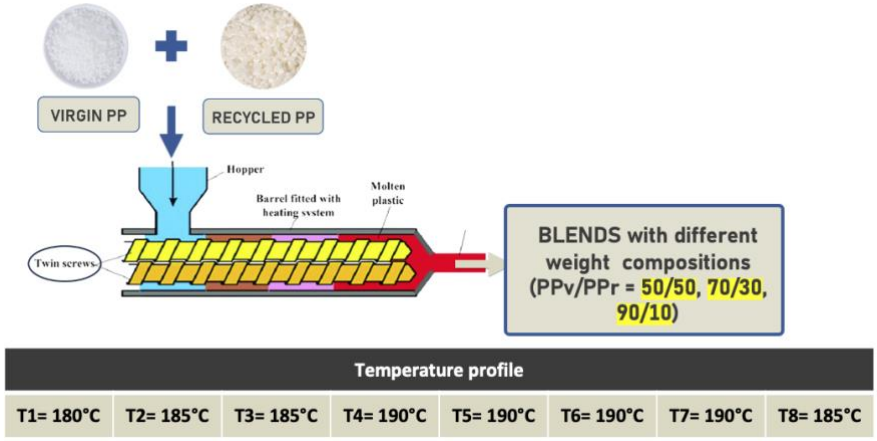
Sample name	Sanitisation technique on recycled fraction	PPv [wt %]	PPr [wt%]
PPv	None	100	0
PPr	None	0	100
US-PPr	Ultrasounds	0	100
HClO-PPr	HClO aqueous solution	0	100
PPv/PPr 90/10	None	90	10
PPv/PPr 70/30	None	70	30
PPv/PPr 50/50	None	50	50
PPv/US-PPr 90/10	Ultrasounds	90	10
PPv/US-PPr 70/30	Ultrasounds	70	30
PPv/US-PPr 50/50	Ultrasounds	50	50
PPv/HClO-PPr 90/10	HClO aqueous solution	90	10
PPv/HClO-PPr 70/30	HClO aqueous solution	70	30
PPv/HClO-PPr 50/50	HClO aqueous solution	50	50

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(a)



Temperature profile							
T1= 180°C	T2= 185°C	T3= 185°C	T4= 190°C	T5= 190°C	T6= 190°C	T7= 190°C	T8= 185°C

(b)

Figure 1 *- Production steps of PPr (a) and PPv/PPr blends (b)*

2.3 Characterisation techniques

2.3.1 ATR-FTIR

Fourier-transform infrared spectroscopy (FTIR) analysis in attenuated total-reflection (ATR) mode was conducted to obtain infrared spectra of the face mask layers, virgin polypropylene, unsanitised and sanitised recycled polypropylene and their blends to assess any degradation phenomena. A Nicolet 600 FT-IR spectrophotometer (Thermo Scientific, Waltham, USA) equipped with the Smart Performer tool was used. The spectra were taken in the frequency range 4000-700 cm^{-1} with a resolution of 2 cm^{-1} and averaged across 64 scans. Normalisation and peak integration were performed using Omnic software.

2.3.2 Differential Scanning Calorimetry

Thermal analysis of the face masks, the neat materials, with the sanitised and unsanitised recycled polypropylene, and the blends were performed using a differential scanning calorimeter (Chip-DSC 100, Linseis Messgeraete GmbH, Selb, Germany) under a constant nitrogen flow (100 mL/min). Each sample was first heated from 25°C to 180°C at a rate of 10°C/min and held at 180°C for 5 minutes.

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This step was followed by cooling from 180°C to 25°C at a rate of 10°C/min, and then a second heating from 25°C to 180°C at the same rate. A heat of fusion for a 100% crystalline PP of 205 J/g was used to calculate the degree of crystallinity [28].

2.3.3 Density

The density of the three face mask layers was measured. The test was conducted using a gravimetric method based on Archimedes' principle, according to the ASTM D972-20, Method B [29]. An analytical balance (mod. BC, ORMA, Milan, Italy) equipped with a Sartorius density determination kit was used, with ethanol serving as the auxiliary liquid, for which the density (ρ_f = 0.78377 g/cm³) was calculated at the test temperature (T = 26.5°C) registered using a thermometer. The density of the samples was calculated using the following formula:

$$\rho = 0{,}0012 + \frac{W_a * (\rho_f - 0{,}0012)}{0{,}99983 * G} \quad (1)$$

where W_a is the weight of the sample in air [g], W_f is the weight of the immersion liquid [g] and G is the hydrostatic force given by (W_a - W_f) [g]. The data reported are the average of six samples.

2.3.4 Rheological characterisation

Dynamic shear rheological analyses were conducted on the virgin mask and the pellets of virgin PP, unsanitised and sanitised recycled PP and blends by using an Advanced Rheometric Expansion System (ARES) (RHEO Service GmbH & Co. KG, Reichelsheim, Germany), equipped with a parallel plate geometry (plate diameter: 25 mm). The complex viscosity, storage and loss moduli were measured at 190°C, from 0.1 to 100 rad/s, with a strain amplitude of 2% to ensure the linear viscoelastic regime for all samples.
The same analyses were performed for the three separate face mask layers by using an Anton Paar MCR 301 Rheometer (Anton Paar GmbH, Graz, Austria), equipped with a more sensible transducer capable of detecting a minimum torque rotation of 0.05 μN/m, compared to the value of 2 μN/m characteristic of the ARES used for the other samples.

2.3.5 Melt flow rate

The melt flow rate (MFR) was measured for the pure materials and the blends by using a Ceast Melt Flow Junior with a 2.16 kg load and a temperature of 230°C, according to the ASTM D1238-13 [30].

2.3.6 Dynamic mechanical analysis

A dynamic mechanical analyser model DMA +50 (Metravib, Limonest, France) was used to perform dynamic mechanical thermal tests (DMTA) in tensile configuration. The test was performed on three specimens obtained by compression moulding (with a width of 10 mm and a height of 30 mm) of each sample from room temperature to 120°C. The heating rate was 2 °C/min. For some samples, the measurement was stopped before reaching 120 °C. The frequency was set at 1 Hz, and a prior static displacement and a dynamic displacement were set at $2x10^{-5}$ m and 10^{-5} m, respectively.

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3. RESULTS AND DISCUSSION

3.1 Characterisation of face masks

Following the removal of the metallic nose wire and elastic ear loops, the fabric material intended for mechanical recycling was characterised. Despite all three layers being extruded together, their separation allowed for an in-depth analysis of each layer and an evaluation of the effects of extrusion on the properties of the recycled material. The inner, middle, and outer layers were individually analysed using ATR-FTIR, and the corresponding spectra are shown in Figure **2**. A detailed peak analysis was conducted to identify the composition of each layer, with the most significant peaks summarised in Table 2. All three layers display characteristic peaks of polypropylene, including CH_2/CH_3 stretching vibration bands around 2900 cm^{-1} and a pair of CH_3 bending/scissoring vibration bands near 1400 cm^{-1}. Additionally, peaks at 1165 cm^{-1}, 998 cm^{-1}, and 971 cm^{-1}, indicative of CH_3 wagging and rocking, provide additional confirmation that the nonwoven fabrics are composed of PP [31,32].

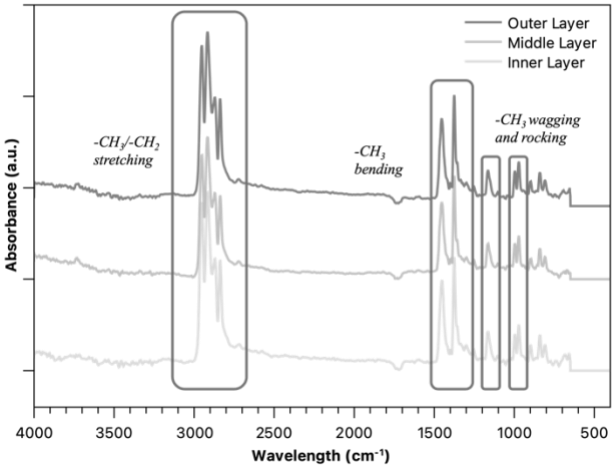


Figure 2 *–ATR-FTIR spectra of face mask layers*

Table 2 *- Assignment of characteristic peaks of face mask layers*

Wavenumber [cm^{-1}]	Associated vibration
2950 and 2865	*Asymm. and symm. -CH_3 stretching*
2920 and 2840	*Asymm. and symm. -CH_2 stretching*
1453 and 1375	*Asymm. and symm. -CH_3 bending*
1165	*-CH_3 wagging*
998 and 971	*-CH_3 rocking*

Table 3 *- Density values of the three layers of the face mask*

SAMPLE	DENSITY [g/cm^3]
INNER LAYER	0.91 ± 0.07
MIDDLE LAYER	0.91 ± 0.07
OUTER LAYER	0.90 ± 0.04

Figure 3 shows the plot of complex viscosity (η*) vs angular frequency (ω) at T = 190°C for the three layers. The viscosity of the middle layer is two orders of magnitude lower than that of the outer and the inner layers, whose curves are practically superimposable and exhibit a more pronounced shear thinning behaviour throughout all the investigated ranges of frequencies. These findings align with the standard PP specifications for 3-ply face mask production. Both the inner and outer layers are made from spun-bond nonwoven fabric, while the middle layer, acting as a filter, is produced using

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the melt-blown technique [33]. The melt-blown process, using PP with a higher MFR (30-1500 g/10 min) and a reduced viscosity [34], creates finer microfibers and smaller pores, ideal for filtration. In contrast, the spun-bond technique for the inner and outer layers requires PP with a lower MFR (12-70 g/10 min) [35].
The thermal analysis is reported in Figure 4. The crystallisation temperature (T_c) observed during the cooling phase is consistent across all layers, recorded at 116°C, indicating uniformity in their composition. This finding is further supported by the subsequent heating phase, where melting transitions were observed between 150°C and 170°C, with peaks at 164°C for the outer layer, 158°C for the middle layer, and 162°C for the inner layer. It's worth noting that the middle layer shows an additional, smaller peak close to the one mentioned above, at around 164°C, indicating a different crystal population as a direct consequence of the different type of polypropylene used for the fabrication of this layer. These temperatures are similar to those reported for PP in other studies [32,36] and align with the assumptions made with the ATR-FTIR analysis.
Finally, the density of the three mask layers was measured, with values of 0.91, 0.91, and 0.90 g/cm³ for the inner, middle, and outer layers, respectively, as shown in Table 3.

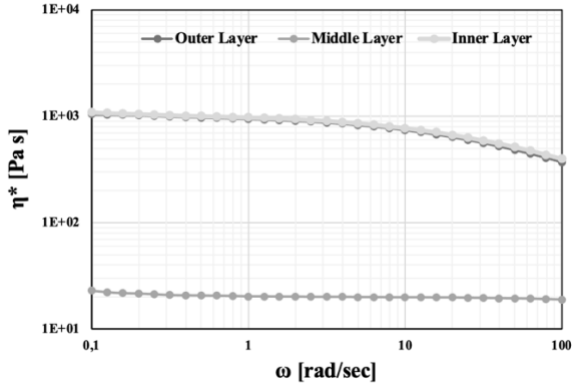


Figure 3 *- Complex viscosity curves at 190°C for the face mask layers*

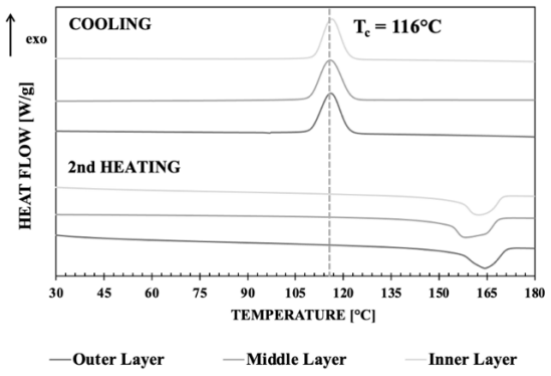


Figure 4 *- 2nd heating and cooling thermogram of inner, middle and outer layers*

Although the three layers of the mask were individually characterised to investigate their properties more thoroughly, they were subsequently mechanically recycled together without any separation. This approach was followed due to the similar composition of the layers (all layers made up of polypropylene) and aims to facilitate potential industrial applicability while simplifying the recycling process. Nevertheless, the careful analysis may prove to be a useful support for subsequent characterisations of the recycled material and its blends.

3.2 Characterisation of recycled materials

The recycled PP (PPr), obtained with the procedure reported in **Error! Reference source not found.**a, was characterised and compared to the initial face masks. While recycling the disposable masks, the polymer structure may have deteriorated. Consequently, FT-IR spectra were meticulously examined for indications of potential oxidation. Literature indicates that during the degradation of PP, major peaks associated with carbonyl groups emerge between 1700 and 1725 cm^{-1} [37]. Additionally, a broad absorption band in the range of 1800 to 1670 cm^{-1} is linked to the presence of lactones, esters, and ketones [38]. Since no notable change is detected in the 1800 to 1600 cm^{-1} range when comparing the spectra of recycled PP (Figure 5) with the original mask layers (Figure 2), it can be concluded that the selected extrusion conditions were appropriate and that the mechanical recycling process did not promote the oxidation of the fabric material. At the same time, to study the

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effect of the chosen sanitisation method, FT-IR spectra were also recorded for the sanitised recyclates, as shown in Figure 5. Furthermore, the peak analysis aligned with that conducted for the study of the outer, middle and inner layers (Table 2) and allowed the conclusion that there was no change in the present functional groups due to the sanitisation processes.

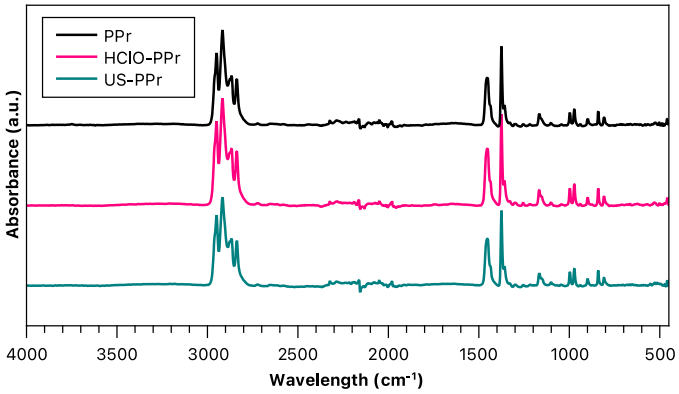


***Figure 5** - ATR - FTIR spectra of processed polypropylenes: PPr, US-PPr, HClO-PPr*

The thermal properties of the samples were analyzed using DSC, with the results presented in Figure 6 and summarized in Table 4. The untreated recycled polypropylene exhibited a higher crystallization temperature (122°C) compared to the initial face mask layers (116°C). Furthermore, the crystallization temperature of the recycled material increased slightly more after the sanitization process. These findings suggest that the thermomechanical stresses during the extrusion process and then the sanitisation treatment contributed to polymer chain breakdown, enhancing chain mobility and facilitating their organization into the crystalline structure [39]. The observed increase in the crystallization temperature could be also attributed to greater exposure of recycled materials to nucleating agents, such as common household dust.
However, no differences were observed between the untreated PPr and the sanitised samples during the second heating scan, as the melting temperature remained consistent at 162°C across all three recyclates. Using a reference melting enthalpy of 205 J/g for 100% crystalline PP, the degrees of crystallinity were calculated as 50.1% for PPr, 42.7% for US-PPr, and 49.0% for HClO-PPr. In the case of sanitised polypropylenes, the crystallinity is slightly more pronounced for the sample treated with HClO, possibly due to the more aggressive action of the chemical treatment employed and/or residual traces of HClO, acting as nucleating agents.

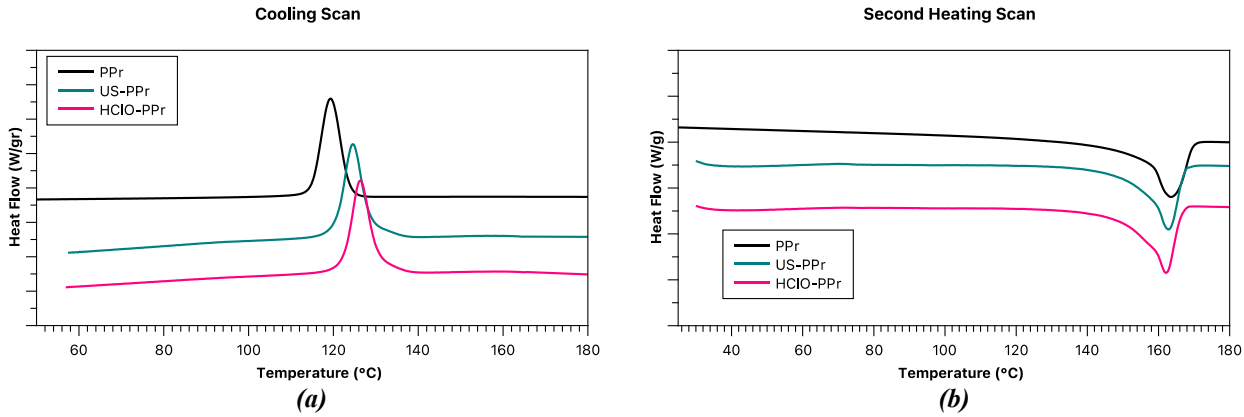


***Figure 6** - Cooling (a) and Second Heating (b) thermograms of recycled materials, unsanitised and sanitised*

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Table 4 *- Thermal transition parameters of recycled materials, unsanitised and sanitised*

	$T_{c,onset}$ [°C]	T_c [°C]	ΔH_c [J/gr]	$T_{m,onset}$ [°C]	T_m [°C]	ΔH_m [J/gr]	χ [%]
PPr	125.0	122.0	-100.7	153.1	162.3	103.7	50.1
US-PPr	128.7	124.6	-108.9	156.4	162. 8	87.7	42.8
HClO-PPr	130.5	126.3	-108.1	155.6	162.1	100.5	49.0

Rheological properties are highly sensitive to the chain length and the molecular weight distribution (MWD) of the polymer. Even minor degradations, that do not alter the functional groups detectable by FT-IR, can reduce the molecular weight leading to changes in rheological behavior. For this reason, complex viscosity curves at 190°C were registered for the virgin mask and all recycled materials (Figure 7). To interpolate the data and extrapolate the Newtonian viscosity (η_0), the Cross equation was applied:

$$\eta = \frac{\eta_0}{[1 + (h * \omega)^m]} \quad (2)$$

where the constant h is a characteristic time of the material, and m is adimensional and related both to the shape of the flow curve at a high shear rate and to the polydispersity [40]. The parameters derived from fitting the experimental data are listed in Table 5.

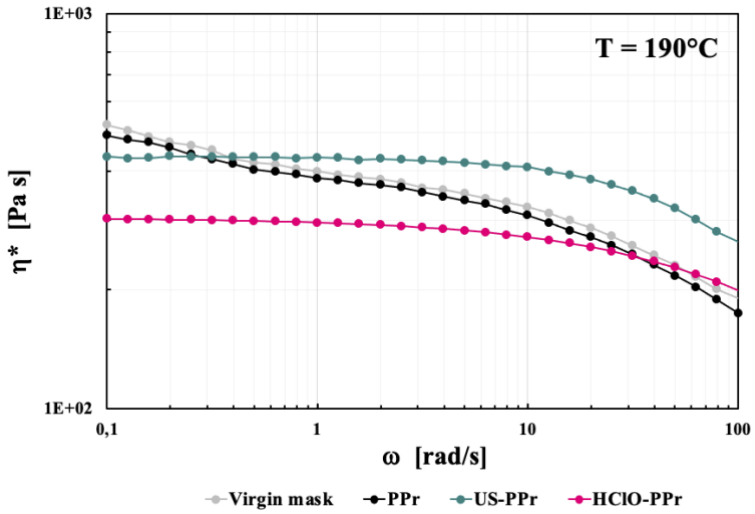


Figure 7 *- Complex viscosity curves at 190°C for virgin mask and unsanitised and sanitised PPr*

The virgin mask and the untreated recyclate exhibited a pronounced shear-thinning behavior with a η_0 of approximately 602 and 564 Pa s (Table 5). The slight reduction registered between the virgin mask and PPr further confirms the minimal degradation experienced by the face masks during the extrusion process as previously assessed by thermal analysis.
Moreover, in Figure 7 the complex viscosity curves of US-PPr and HClO-PPr are also reported. As can be observed, both sanitisation methods reduced viscosity values and altered the shape of the curves, extending the Newtonian plateau. In particular, the viscosity progressively decreases from 602 Pa s (virgin mask) to 304 Pa s (HClO-PPr). This trend is consistent with the fact that recycling and sanitisation can reduce molecular weight and viscosity, particularly with processes such as chemical sanitisation (HClO-PPr). Additionally, from Table 5 it can be observed that h decreases significantly in the sanitised materials, with its value being very small for US-PPr (0.007 s) and

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HClO-PPr (0.004 s). This behavior indicates that the treatments drastically reduced the characteristic time of viscous relaxation, consistent with a loss of molecular entanglements due to a reduction in molecular weight. Due to the extension of the Newtonian plateau, a cross-over point is observed between the curves of the sanitised samples and the untreated recyclate, occurring at ω=0.03 rad/s and ω=35 rad/s, for US-PPr and HClO-PPr, respectively. Beyond this point, the viscosity values of the sanitised samples exceed those of the PPr. The extension of the Newtonian plateau is related to factors that reduce molecule interactions and enhance the mobility of polymer chains, such as a decrease in molecular weight, a narrow molecular weight distribution and the presence of plasticizers.
Dynamic rheological tests also allowed the evaluation of the storage modulus G' and the loss modulus G''. Results revealed a reduced elasticity for the sanitised recycled materials (Figure 8). The intersection of the two curves is not visible within the examined frequency range for the recycled polymers, suggesting that in the observed range of frequency the materials exhibit a liquid-like behaviour (with G''>G'). To estimate the crossover point, the general trend of the curves was interpolated using second-order polynomial fits. By extending the frequency axis based on these fits, the intersection points were determined to occur at frequencies of 251 rad/s for PPr and 316 rad/s for both US-PPr and HClO-PPr. The different positions of the cross-over point provide insight into differences in molecular weight or molecular weight distribution. Specifically, the gradual shift to higher frequencies in the sanitised recycled materials with respect to the virgin mask (ω_c = 79 rad/s) suggests a shorter polymer chain length and a lower molecular weight [27] [40], highlighting the slight degradation induced by the extrusion and the sanitisation method.
Additionally, the cross-over coordinates were correlated with molecular structure parameters using the empirical equation P.I. = $10^5/G_c$ which defines the polydispersity index on the basis of the cross-over modulus [41,42]. The calculated values are presented in Table 5 and indicate a narrower molecular weight distribution for the sanitised recyclates with respect to the initial face mask and the untreated PPr [43]. The P.I. value goes from 3.2 (virgin mask) to 2.3-2.4 (sanitised materials) with a plausible decrease considering that sanitisation or recycling processes often remove the high molecular weight fractions. The lower values calculated for US-PPr and HClO-PPr support the observed changes in the shape of the complex viscosity curves: the narrowing of the MWD enhances the Newtonian characteristics, extending the plateau and reducing the shear-thinning behaviour [44].

Table 5 *- Characteristic rheological parameters for Eq. 1, cross-over point coordinates and polydispersity index for virgin masks and unsanitised and sanitised PPr*

	η_0 [Pa s]	h [s]	m [-]	ω_c	G_c	P.I.
Virgin mask	602	0.081	0.31	79	28219	3.2
PPr	564	0.074	0.33	251	34508	2.9
US-PPr	434	0.007	0.99	316	42927	2.3
HClO-PPr	304	0.004	0.64	316	42001	2.4

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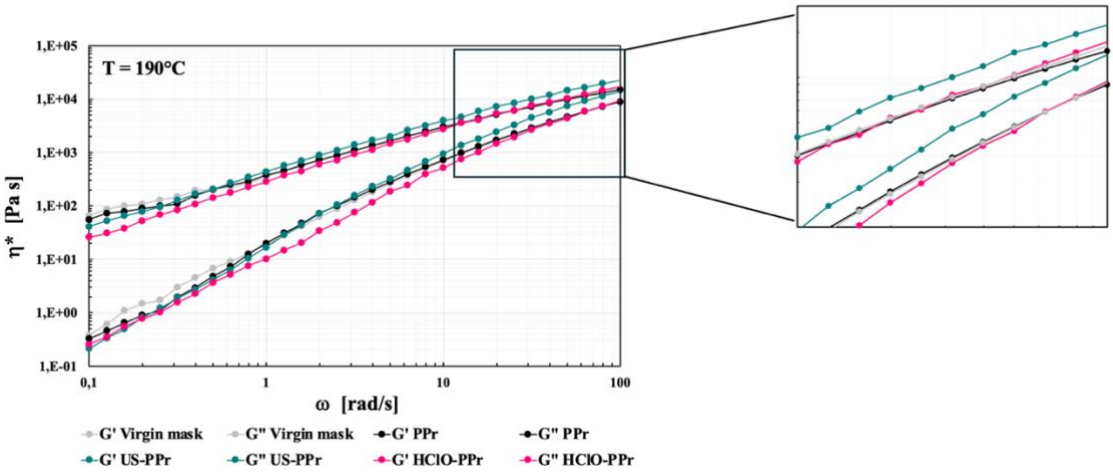


Figure 8 *- G', G'' [Pa] vs ω [rad/s] plots at 190°C for the virgin mask, PPr, US-PPr and HClO-PPr*

Regarding the mechanical behaviour, dynamic mechanical measurements were carried out as a function of temperature. The general result shown is that the modulus E' at 25°C for the recycled PP is equal to 1.42 GPa. With respect to the untreated sample, the physical treatment increases the modulus at 25°C and the chemical treatment decreases the modulus, 1.55 GPa and 1.42 GPa for US-PPr and HClO-PPr respectively. In addition, the transition temperature at which the damping factor shows a peak in its curve is shown in the table, where it is highlighted that recycling combined with ultrasound or chemical treatment reduces this temperature with respect to the untreated sample. These results are perfectly in agreement with those obtained using the other characterisation method mentioned above.

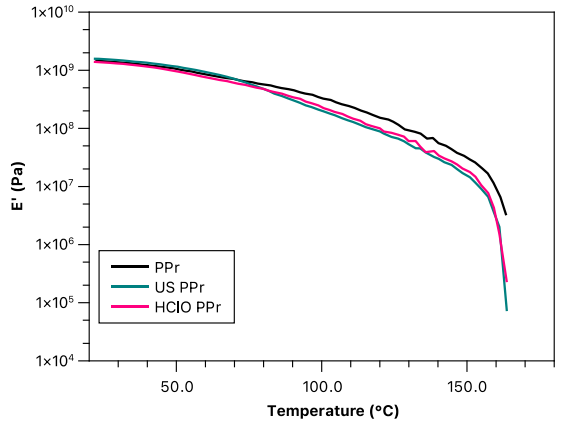


Figure 9 *- E' [Pa] vs Temperature [°C] for recycled materials*

Table 6 *- E' [MPa] at 25°C and the temperature relative to the maximum of tanδ*

	$E'_{25°C}$ [MPa]	$T_{tan\delta,max}$ [°C]
PPr	1.4×10^3	118.1
US-PPr	1.5×10^3	115.1
HClO-PPr	1.3×10^3	115.8

In light of these findings, it is essential to improve the viscosity and overall rheological and mechanical properties of recycled polypropylene so that it can be reused in processes such as cast film extrusion or material extrusion-based additive manufacturing. To achieve this goal, a strategy must be implemented to improve material performance during these conversion processes. Previous studies indicate that minimising the melting and crystallisation enthalpy while improving the shear thinning behaviour and yield stress is crucial to making PP-based materials suitable for additive manufacturing [45–49]. Despite the influence of other factors, e.g., crystallinity, commercially

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available PP filaments for Fused Filament Fabrication (FFF) typically have MFIs in the range of 5 to 13 g/10 min [23], significantly lower than the value observed for the recycled material in this study. Higher MFR values can be found when using granulate feedstock for material extrusion-based additive manufacturing, e.g., Fused Granular Fabrication (FGF), which usually relies on direct feeding screw-assisted systems [50]. Nevertheless, minimising the feedstock crystallisation after deposition significantly improves the overall quality of the 3D printed parts, reducing warping and nozzle [51] clogging for both filament and granulate-based processes. Similarly, rheological properties influence the performance of cast films. In particular, increasing melt elasticity during cast film extrusion can reduce neck-in phenomena, improve film stability and promote greater thickness uniformity [52]. The elasticity of the melt causes the film exiting the slit die to expand, counteracting the stretching effect as the geometric constraint is removed and helping to maintain the desired dimensions of the material [53].

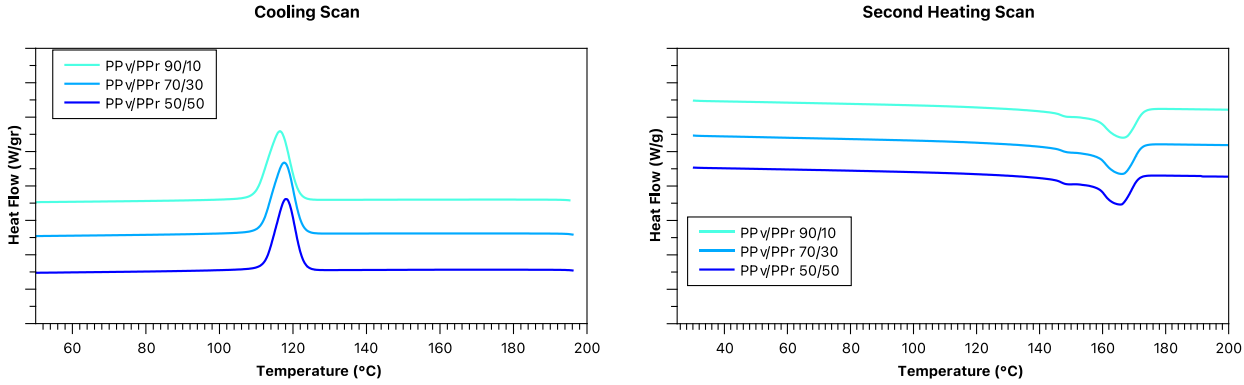
From this point of view, a simple solution is to produce blends of untreated or sanitised recyclate and virgin PP [54]: this approach makes it possible to tune the rheological properties of the recycled material, improving its performance and compatibility with conventional manufacturing processes while reducing the costs associated with the use of large quantities of virgin polymer.

3.3 Characterisation of PPv/PPr blends and effect of sanitisation

Recognising the importance of blend formulations and targeting the desired applicability in cast film extrusion and additive manufacturing, a virgin PP (PPv) graded for film extrusion was selected. PPv/PPr blends at three different compositions were produced and compared, with a focus on the differences between unsanitised (PPv/PPr 90/10, PPv/PPr 70/30, PPv/PPr 50/50) and sanitised recyclate, treated by ultrasounds (PPv/US-PPr 90/10, PPv/US-PPr 70/30, PPv/US-PPr 50/50) and HClO solution (PPv/HClO-PPr 90/10, PPv/HClO-PPr 70/30, PPv/HClO-PPr 50/50).
Firstly, to evaluate the impact on the resulting systems, the virgin PP was thoroughly characterised before blending through thermal, rheological and mechanical analyses.
For the sake of brevity, only the thermograms of the pure PPv/PPr blends are shown in Figure 10 , while the processed data for all blends are shown in Table 7. Thermal analysis of the samples indicated that the crystallisation temperature increased with the gradual addition of PPr to the blend, suggesting a higher proportion of shorter polymeric chains. Initially, the virgin polymer exhibited a T_c of 116.7 °C. As recyclate was incorporated, the crystallisation temperature rose progressively, reaching 117.7 °C, 118.8 °C, and 119.3 °C for blends containing 10 wt.%, 30 wt.%, and 50 wt.% of PPr, respectively. For blends obtained by using US-PPr or HClO-PPr as a diluent to virgin polypropylene, the crystallisation temperature decreases, achieving a value of ≈ 113 °C, lower than the ones of PPv and both US-PPr and HClO-PPr.
During the second heating, all blends showed two melting peaks. The first small peak is between 149 and 153 °C, which can be related to the crystalline β-phase of polypropylene [43,55]. The more pronounced peak for the PPv/PPr blends is at a temperature comparable to the melting temperature of PPv, indicating that the crystallisation behaviour is more controlled by the presence of PPv. For the PPv/US-PPr and PPv/HClO-PPr blends, the melting temperature is around 162°C, indicating that the thermal behaviour is more similar to the treated recycled polypropylene. Finally, as regards the degree of crystallinity of the blends, it appears that the treated recycled polymers (US-PPr and HClO-PPr) act as nucleating agents when they are the minor phase in the blend, with respect to when they are the half amount of the blend in which the degree of crystallinity appears comparable to the relative treated matrix.

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(a) ***(b)***

Figure 10 *- Thermograms of Cooling and Second Heating Scan of (a-b) PPv/PPr blends*

Table 7 *- Main Thermal Properties of Cooling and Second Heating Scan*

	$T_{c,onset}$ [°C]	T_c [°C]	ΔH_c [J/gr]	$T_{m,1}$ [°C]	$T_{m,2}$ [°C]	ΔH_m [J/gr]	χ [%]
PPv	120.4	116.7	-86.6	167.4	-	82.6	39.9
PPv/PPr 90/10	121.9	117.7	-87.5	149.2	165.4	75.3	36.7
PPv/PPr 70/30	122.8	118.8	-88.4	148.5	168.2	90.1	43.9
PPv/PPr 50/50	123.1	119.3	-82.6	149.7	166.9	83.7	40.8
PPv/US-PPr 90/10	118.4	112.8	-103.4	153.3	162.9	98.3	47.9
PPv/US-PPr 70/30	118.9	112.8	-105.3	152.9	161.8	98.8	47.2
PPv/US-PPr 50/50	118.6	113.3	-105.7	149.8	161.9	91.6	44.7
PPv/HClO-PPr 90/10	117.5	112.6	-110.4	151.4	161.2	103.4	50.4
PPv/HClO-PPr 70/30	118.6	113.5	-110.6	149.6	165.1	106.5	51.9
PPv/HClO-PPr 50/50	118.5	113.6	-98.5	152.2	161.8	91.7	44.7

Complex viscosity curves of unsanitised blends obtained at 190°C are reported in Figure 11. As shown, all blends show intermediate viscosity values between the ones of the two components (PPv and PPr) across the entire frequency range [40]. Increasing the recyclate content from 10 to 50 wt.% led to a gradual decrease in viscosity, primarily due to the plasticizing effect of the PPr, characterized by a lower molecular weight and significantly higher fluidity. As for the pure components, the Cross model was used for interpolating the data and extrapolating the Newtonian viscosity (Table 8) for the blends, highlighting its gradual decrease for increasing concentrations of recycled polymer. Specifically, a reduction of 15%, 37 % and 57% for η_0 with respect to the neat PPv was registered for PPv/PPr 90/10, PPv/PPr 70/30 and PPv/PPr 50/50, respectively.
Similarly, the elastic modulus G' gradually decreases as the amount of recycled PP in the blend moves from 10 to 50 wt% [40], shifting the cross-over point, detectable for the virgin PP at 79 rad/s, to higher frequencies outside the investigated range (Table 8) and confirming the addition of rising concentrations of a low molecular weight polymer.

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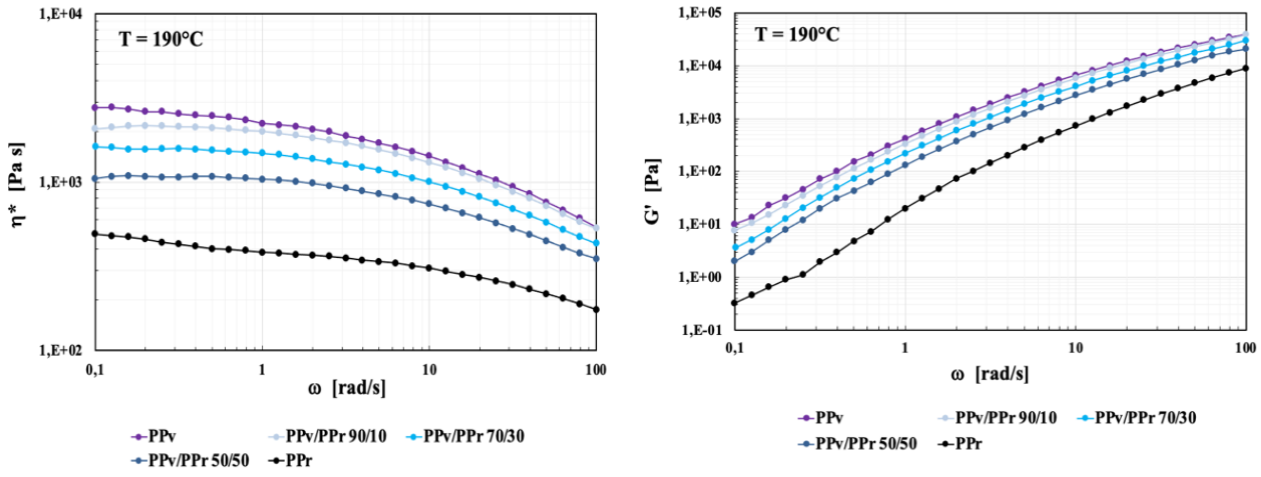


Figure 11 *- Viscosity [Pa s] vs ω [rad/s] (a) and G', G'' [Pa] vs ω [rad/s] (b) plots at 190°C for the PPv, PPr and their blends*

The same curves were registered for the sanitized blends at 190°C. Characteristic rheological parameters are reported in Table 8 and can be compared to the ones of the pure blends to assess the impact of the selected sanitization method.
For all three compositions, the sanitization process reduced the viscosity of the blends, shifting the curves to lower values. Specifically, the use of ultrasound treatment had a milder effect, lowering the η_0 values from 2241 to 1855 Pa·s for the 90/10 composition, from 1667 to 1350 Pa·s for the 70/30 composition, and from 1123 to 931 Pa·s for the 50/50 composition (Table 8). This reduction was accompanied by a gradual increase in the cross-over frequency for rising concentrations of recyclate, suggesting polymer degradation and a decrease in molecular weight. A similar trend was observed for the blends treated with aqueous HClO solution, which also exhibited reduced viscosity and increased ω_c with increasing recyclate content. Notably, the chemically treated blends showed a further reduction in Newtonian viscosity, with values of 1400.1, 1060.4, and 868.0 Pa·s for the 10%, 30%, and 50% recycled polypropylene compositions, respectively.

Table 8 *- Characteristic rheological parameters for Eq. 1, cross-over point coordinates and polydispersity index for PPv and all blends*

	η_0 [Pa s]	h [s]	m [-]	ω_c	G_c	P.I.
PPv	2936	0.120	0.58	79	34245	2.9
PPv/PPr 90/10	2241	0.059	0.70	126	41651	2.4
PPv/PPr 70/30	1667	0.052	0.67	159	41283	2.4
PPv/PPr 50/50	1123	0.036	0.70	316	45583	2.2
PPv/US-PPr 90/10	1855	0.065	0.64	126	33322	3.0
PPv/US-PPr 70/30	1350	0.051	0.64	251	37487	2.7
PPv/US-PPr 50/50	931	0.045	0.55	501	42606	2.3
PPv/HClO-PPr 90/10	1400	0.053	0.55	159	35003	2.9
PPv/HClO-PPr 70/30	1060	0.042	0.56	398	37993	2.6
PPv/HClO-PPr 50/50	868	0.053	0.67	631	39990	2.5

The MFR values for all samples evaluated at 230°C are presented in Table 9 and support the previous observations regarding viscosity. Starting with the virgin polymer, which had an MFR value of 9 g/10 min, as confirmed by technical data sheet, it is evident that fluidity progressively increased with a higher content of recycled material, confirming the plasticisation effect of the recyclate. The presence of shorter polymer chains reduces the development of entanglements and weakens intermolecular

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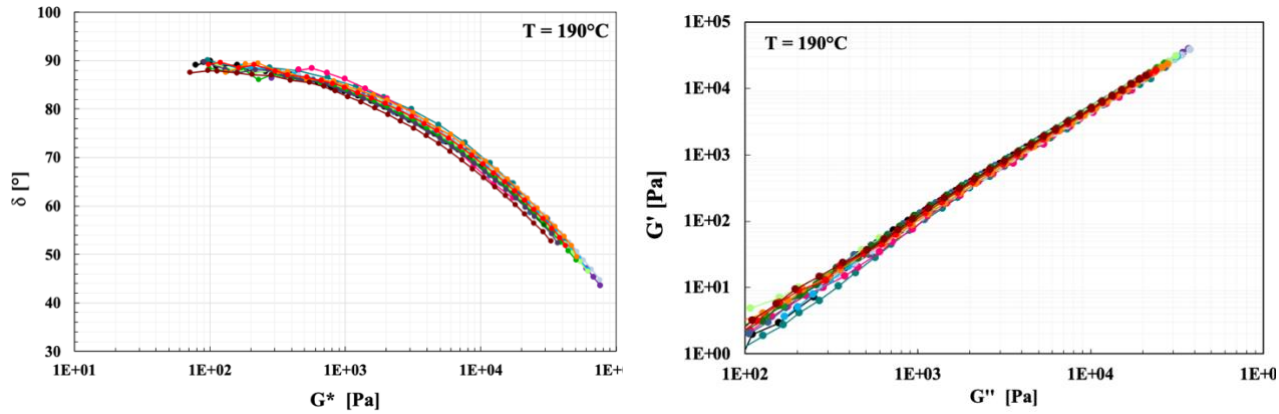
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interactions, enhancing the mobility and flow capability of the blends. This fact is reflected in the higher MFR values, consistent with the viscosity reduction observed in the rheological analysis [23]. As previously observed for the viscosity, the chemical treatment carried out on the PPr affected the blends by improving the fluidity and resulting in MFR values that increased from 10.9 to 14.4 g/10 min, from 15.9 to 20.1 g/10 min and from 18.3 to 24.2 g/10 min for 10%, 30%, and 50% wt.% of recyclate, respectively. Conversely, ultrasound treatment showed no effect on the fluidity of blends with less than 50 wt.% recycled material, leaving the MFR values unchanged.

Table 9 *- MFR [g/10 min] for PPv and the blends*

	MFR [gr/10min] 2.16 kg, @230°C
PPv	9.0 ± 0.1
PPv/PPr 90/10	10.9 ± 0.4
PPv/PPr 70/30	15.9 ± 1.0
PPv/PPr 50/50	18.3 ± 1.7
PPv/US-PPr 90/10	10.4 ± 1.4
PPv/US-PPr 70/30	14.5 ± 2.0
PPv/US-PPr 50/50	22.7 ± 2.0
PPv/HClO-PPr 90/10	14.4 ± 1.2
PPv/HClO-PPr 70/30	20.1 ± 1.7
PPv/HClO-PPr 50/50	24.2 ± 2.3

Van-Gurp Palmen plots and Han plots were studied to evaluate the miscibility of PPr, sanitised using ultrasounds and hypochlorous acid solution, when blended with virgin PP. These analyses could provide a detailed understanding of how the sanitisation processes influenced the molecular interactions, phase behavior, and overall compatibility of the blend components. Based on rheological data, the miscibility of the blend components was also assessed. Firstly, Van-Gurp Palmen plots (Figure 12a) were investigated: the analysis evaluated the phase angle (δ) as a function of the complex modulus (G*). According to the literature, for single-phase systems, the value of δ approaches 90° at the lowest values of G* [56]. This condition was satisfied for all blends, with their plots aligning closely with those of the pure components. Further support for this observation comes from the Han plots (Figure 12b). Indeed, in miscible polymer blends, Han plots are composition-independent and display identical slopes, as illustrated in Figure 12b, where all curves overlap [57].



(a) *(b)*

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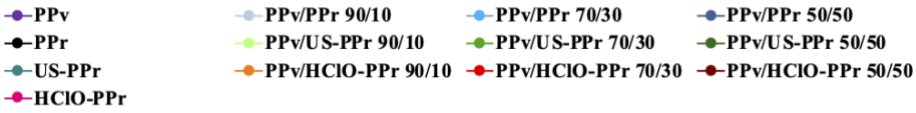


Figure 12 *- Van-Gurp Palmen (a) and Han (b) plots for the neat components and the blends*

Regarding the mechanical behaviour, dynamic mechanical measurements were carried out as a function of temperature (see **Error! Reference source not found.**). Observations for blended compositions compared to the corresponding pure materials are provided in this section. The modulus at 25°C is consistently lower in all virgin/recycled polypropylene blends compared to the corresponding recycled polypropylene alone, regardless of whether the recycled material has been sanitised. However, the blend formulations have a higher E' modulus at 25°C than virgin polypropylene, indicating a higher stiffness. In terms of the temperature at which the damping factor shows a peak in its curve, the addition of 10 wt.% recycled PP to virgin polypropylene reduces the damping factor peak temperature, suggesting a plasticising effect. At higher recycled PP contents (30 wt.% or 50 wt.%), the peak temperature increases compared to the 10 wt% blend but remains lower than that of the virgin materials. This trend highlights a reduction in mechanical stability with temperature for the blended compositions.

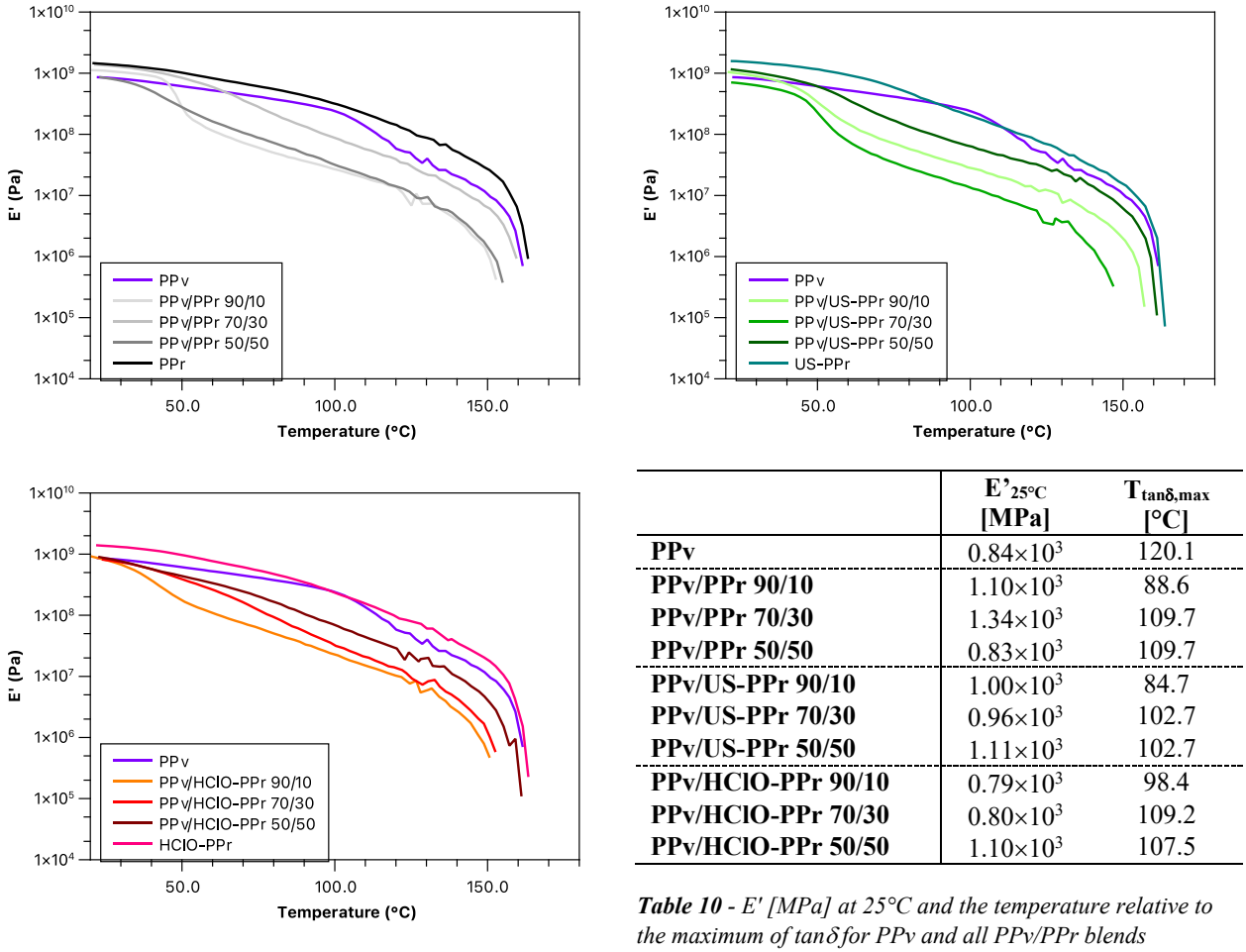


Figure 13 *- E' modulus as a function of temperature*

	$E'_{25°C}$ [MPa]	$T_{tan\delta,max}$ [°C]
PPv	0.84×10^3	120.1
PPv/PPr 90/10	1.10×10^3	88.6
PPv/PPr 70/30	1.34×10^3	109.7
PPv/PPr 50/50	0.83×10^3	109.7
PPv/US-PPr 90/10	1.00×10^3	84.7
PPv/US-PPr 70/30	0.96×10^3	102.7
PPv/US-PPr 50/50	1.11×10^3	102.7
PPv/HClO-PPr 90/10	0.79×10^3	98.4
PPv/HClO-PPr 70/30	0.80×10^3	109.2
PPv/HClO-PPr 50/50	1.10×10^3	107.5

Table 10 *- E' [MPa] at 25°C and the temperature relative to the maximum of tanδ for PPv and all PPv/PPr blends*

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4. CONCLUSIONS

This study investigated the recyclability of the 3-ply disposable surgical face masks through extrusion, focusing on recovering polypropylene as a valuable materials for alternative applications. A central aspect of this work was the evaluation of sanitisation process, which are critical for reducing microbiological contamination while preserving material integrity.
The results demonstrated that the two selected sanitisation methods - ultrasound treatment and aqueous hypochlorous acid (HClO) solution - did not induce significant chemical degradation, as confirmed by FTIR analysis. No evidence of oxidation or the formation of new functional groups was observed, indicating that these sanitisation steps effectively preserved the chemical structure of PP. However, rheological analyses revealed polymer chain scission and a consequent reduction in molecular weight, which was more pronounced in the HClO-treated sample, highlighting a potential trade-off between effective sanitisation and material degradation. Furthemore, mechanical analysis (DMA) highlighted a general stiffening of PP after recycling, with a more pronounced effect in the chemically treated sample.
Subsequently, thermal, rheological, and mechanical characterization of the blends was conducted to evaluate the impact of incorporating recycled polypropylene (PPr), untreated or sanitised, into a virgin polypropylene (PPv) matrix designed for film extrusion. The composition of the blends significantly influenced the extent of property modifications, with PPv playing a key role in stabilising the performance of the recyclates.
SC analysis demonstrated that the addition of PPv effectively tuned the thermal properties of the recyclates, allowing them to meet the requirements of conventional transformation processes. Rheological characterization revealed significant improvements in viscosity and elasticity with increasing PPv content, while confirming the miscibility of blend components. The effects of sanitisation methods were particularly evident in the rheological properties. Blends containing HClO-treated PPr exhibited greater fluidity, consistent with the more pronounced degradation observed during sanitisation. In contrast, ultrasound-treated samples maintained more stable rheological characteristics, especially at lower PPr concentrations (10% and 30%), ensuring that the required melt flow rate (MFR) values for cast film extrusion and additive manufacturing applications were achieved. DMA results further emphasized increased stiffness in blends with higher recycled content, especially in samples sanitised using ultrasound.
In conclusion, these results suggest that PPr recyclates, sanitized or not, when incorporated into a PPv matrix at controlled concentrations, provide a balanced combination of stiffness and processability, making them particularly suitable for industrial applications. This study highlights a practical pathway for transforming disposable mask waste into valuable industrial resources, contributing significantly to circular economy strategies by reducing plastic waste and promoting sustainable materials management.

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