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SUPPORTING INFORMATION

A new generation of hollow polymeric microfibers produced by gas dissolution foaming

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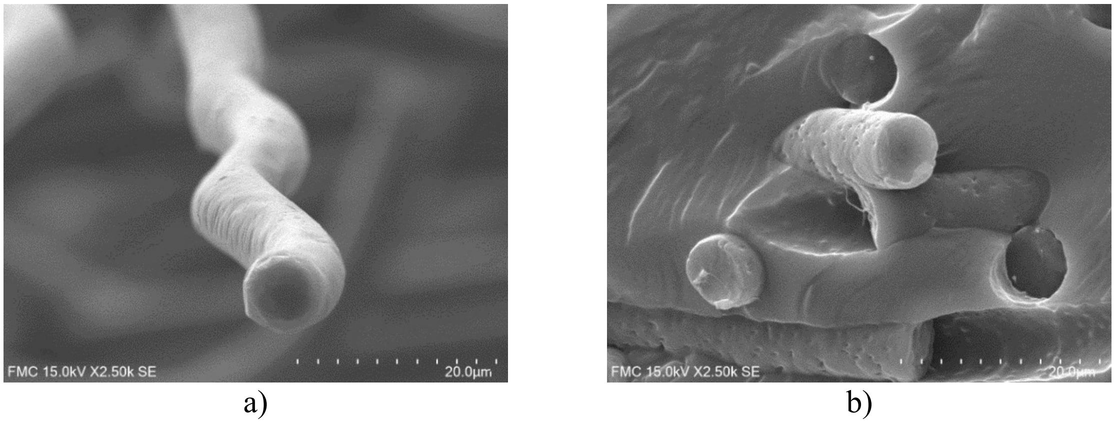
S.I-1. GAS DISSOLUTION FOAMING PROCESS USING DIFFUSION BARRIERS

The gas dissolution foaming process is commonly used in porous polymers fabrication. Also, it is considered a versatile and green method that allows manufacturing polymer foams from several different polymers, even achieving nanoporous materials. However, gas dissolution foaming presents certain limitations. For example, it exists a diameter threshold below which polymers particles or fibers cannot foam due to the gas diffusivity out of the sample prior to the nuclei and pore formation. Thus, polymeric particles or fibers with micrometric or even nanometric dimensions do not become porous polymers by using this foaming approach because gas solubility at the foaming time is not enough to promote the nucleation and the pore growth.

In order to overcome this limitation, we have incorporated a novel approach to the gas dissolution foaming process, which eliminates the diameter limitation of this method. It consists of covering the fibers with a polymer to create a gas diffusion barrier able to decrease the gas diffusion out of the samples after the saturation stage.[1] Polyvinyl alcohol (PVOH) (PVOH) was chosen due to its very low diffusivity of CO_2 and their high solubility in water, which allows removing this layer easily after the foaming process. In this way, the gas introduced in the saturation step remains inside the fibers for a longer time. Therefore the CO_2 solubility at the foaming step is higher and enough to reach the nucleation and pore growth. So, the combination of the PVOH technique with the gas dissolution foaming process has resulted in an interesting method to achieve cellular polymers regardless of the thickness of the solid system.



a) b)

Figure S1. Cross-section of a pristine solid PCL fiber (a) and PVOH-imbibed PCL fibers (b).

Figure S1 shows the cross-section of a pristine fiber and a film of PVOH with imbibed fibers. The coating process was carried out by the solvent casting method, introducing the fibers math into an aqueous solution of PVOH. After water evaporation, fibers math was encapsulated into a PVOH film. As shown in **Figure S.1**, fibers are individually and entirely covered by the polymer one by one. After the foaming procedure, this PVOH layer was easily removed, as shown in **Figure 2, S3,** and **S5.**

S.I-2 RAMAN SPECTROSCOPY

The surface of the individual fibers was studied by Raman spectroscopy using a high-resolution Horiba - Jobin Yvon LABRAM HR 800 UV Raman spectrometer, with an Olympus BX41 microscope and a Symphony CCD detector (microscopic backscattering mode with x100 magnification). The λ = 532.8 nm line from a solid-state laser was used as the exciting beam. The nominal laser power on the sample is 1 mW, with an approximate irradiance of 100 kW·cm^{-2}. The acquisition time was set at 60 s, and the equipment was calibrated with the ν (Si-Si) mode at 520.7 cm^{-1}.

The external surface of solid, hollow, and hollow+porous PCL fibers, as well as of solid PCL fibers imbibed in PVOH, was analyzed (in the case of the foamed fibers after the removal of the PVOH layer), obtaining Raman spectra from different points of different individual fibers of each kind. No differences were found between the solid PCL fibers and the foamed fibers, as **Figure S2** shows. Therefore, it was proved that the PVOH layer was successfully removed, with no significant remains of PVOH on the external surfaces of the foamed PCL fibers (Figure S2 shows the absence of the PVOH Raman spectrum features on the foamed fibers).

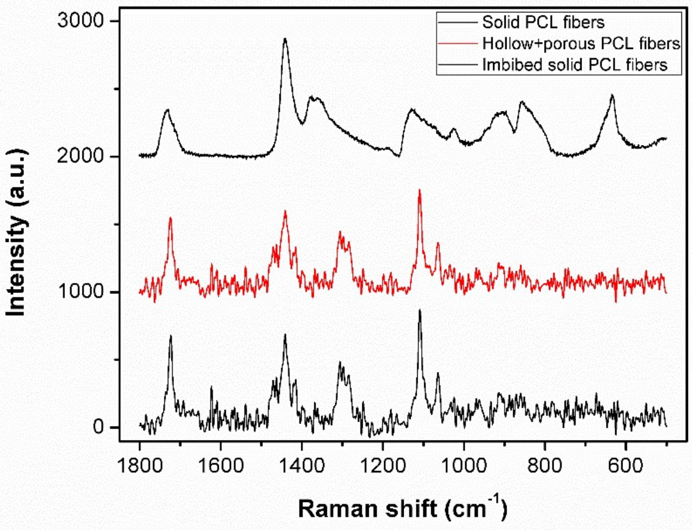


Figure S2. Raman spectra of the solid, hollow+porous, and imbibed PCL fibers.

S.I-3 OPTIMIZATION OF THE FOAMING PARAMETERS

As explained in the results section, hollow and hollow+porous fibers have been obtained for the first time by gas dissolution foaming. Although the foaming parameters related in the experimental section were optimized in order to show the best results, hollow fibers were obtained using a wider range of parameters.

In all the cases, the saturation pressure was fixed in 30 MPa in order to maximize the amount of gas introduced into the fibers. Besides, saturation time was established at 24 hours to ensure the complete saturation of the fibers imbibed into the PVOH. On the other hand, saturation temperature was varied 25 to 60 °C, and two different methods of foaming were employed: one-step foaming and two-step foaming.

First of all, it is necessary to understand the mechanisms involved in the gas dissolution foaming and know the reason why fibers can foam. During the pressure test, gas is introduced into the PCL fibers and promotes a plasticization effect decreasing the melting point, which at atmospheric pressure is about 61 °C for the employed PCL. So, in the desorption step, the CO_2-saturated polymeric sample is under this plasticization effect. Then, if the saturation temperature is higher than its actual melting point (effective melting point), fibers can foam spontaneously at the desorption step (one-step foaming). In contrast, if the saturation temperature is lower than the effective melting point, it is necessary to introduce the sample into a hot bath. Thus, fibers can foam (two-step foaming). In fact, both kinds of foaming fibers were presented in the results section in the same way.

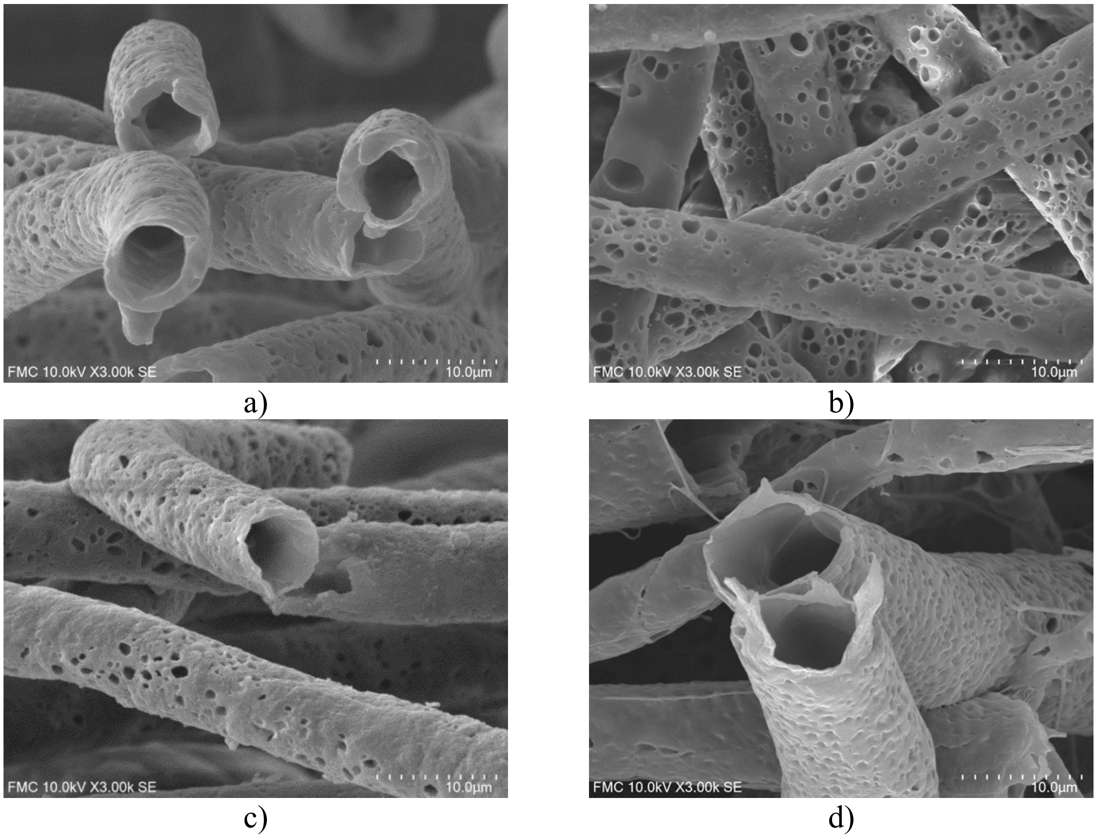
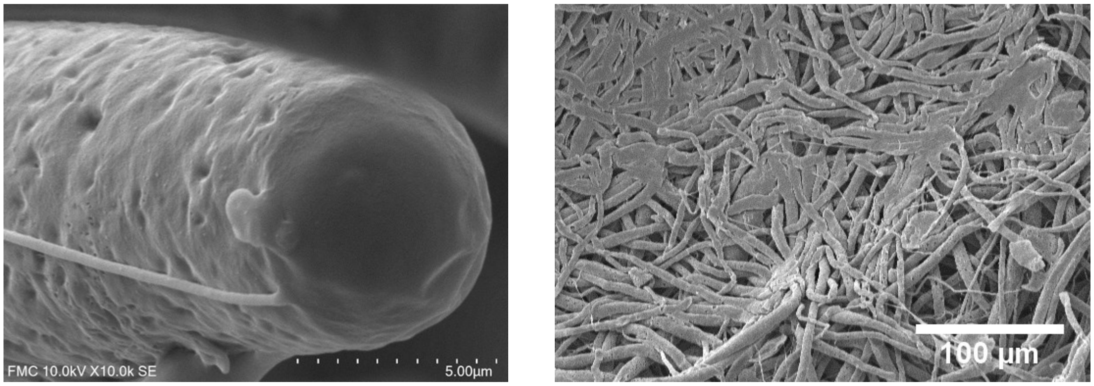


Figure S3. One-step foaming fibers at different saturation temperatures: 45 °C (a), 50 °C (b), 55 °C (c), and 60 °C (d).

First, SEM micrographs of one-step foaming fibers are presented in **Figure S3**. Using this procedure, without introducing the fibers into a heated bath after being extracted from the pressure vessel, it was not possible to obtain foamed fibers below 45 °C of saturation temperature, as shows **Figure S4.**a (i.e., the effective melting point of the PCL saturated with CO_2 at 30 MPa should be around 45 °C). Between 45 and 60 °C, fibers with an inner hole and porosity on the surface were achieved. At higher saturation temperatures above 60 °C, fibers are over its original melting point; thus, during and after foaming procedure, they can melt. **Figure S4.b** shows a micrograph of the surface of a PCL fibers mat, which was attempted to foam above 60 °C of saturation temperature. As expected, the fibers were partially melted and merged.

The best results, in terms of the hollow+porous fibers quality (i.e., absence of defects or degradation and presence of surface porosity) the lower saturation temperature, 45 °C, was determined as optimal, as the progressive increase of saturation temperature lead into the appearance of defects and the decrease of the surface porosity (**Figure S3**).

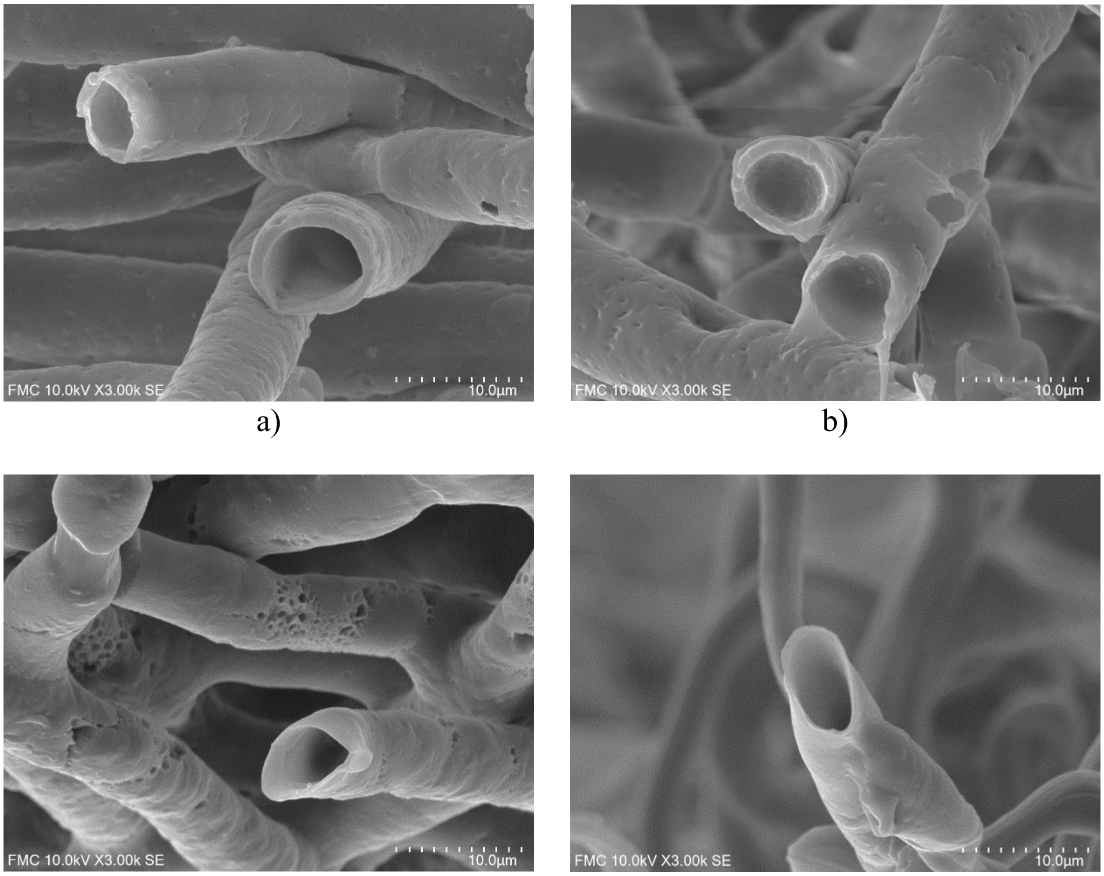


a) b)

Figure S4. SEM micrographs of PCL fibers after being subjected to a one-step foaming procedure at saturation pressure of 30 MPa and temperatures of 40 °C (a) and above 60 °C (b).

On the other hand, the two-step foaming technique allows us to obtain hollow fibers while keeping the original morphology of the surface of the fibers. Hollow fibers were fabricated by two-step foaming in a wide range of saturation temperatures, from 25 to 55 °C (**Figure S5**). In this case, the foaming is carried out in a hot bath (60 °C in all samples) after extracting the samples from the pressure vessel. It was found that the increase of the saturation temperature induced the presence of defects on the obtained foamed fibers (see **Figure S5**), probably due to the partial melting of already foamed fibers. As explained before, saturation temperatures over 45 °C induce the foaming of the fibers without the need for additional heating. Thus, the additional foaming stage by heating of the already foamed fibers could easily damage the thin walls of the foamed fibers.

Moreover, it should be taken into account that this additional foaming stage eliminates the surface porosity of the fibers foamed at saturation temperatures over 45 °C.



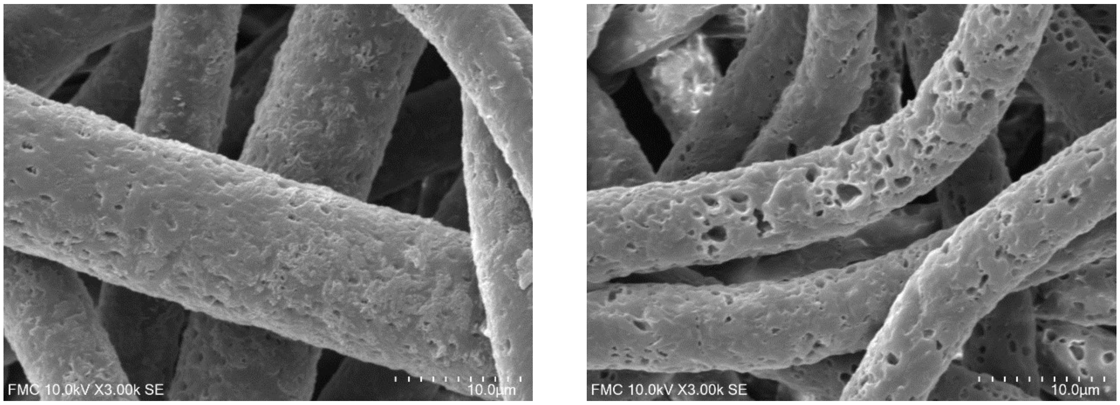
a) b)

c) d)

Figure S5. Two-step foamed fibers at different saturation temperatures: 25 °C (a), 50 °C (b), 55 °C (c), and 60 °C (d).

S.I-4 IBUPROFEN LOADING OF PCL FIBERS

As explained in the Experimental and Results section, the PCL fibers (solid, hollow, and hollow+porous) do not suffer any morphological alteration due to the Ibuprofen impregnation procedure (**Figure S6**). Moreover, it was found that after the impregnation procedure, some Ibuprofen precipitates over the fiber mats (**Figure S7**), being necessary to clean the samples with pressurized air to remove this non-impregnated Ibuprofen.



a) b)

Figure S6. SEM micrographs of hollow (a), and hollow+porous (b) PCL fibers after the Ibuprofen impregnation procedure.

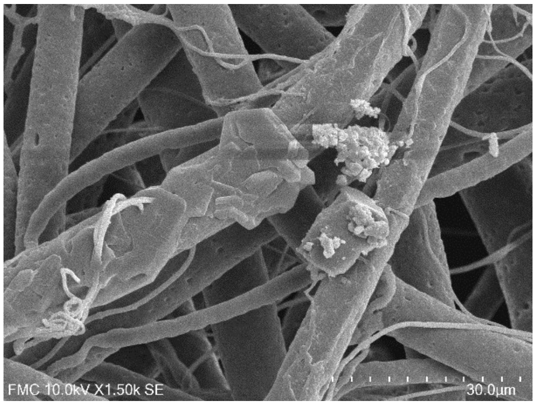


Figure S7. SEM micrographs of Ibuprofen-impregnated PCL fibers before being cleaned by pressurized air, showing Ibuprofen crystals on their surface. It should be noticed that these preliminary tests without removing the precipitated Ibuprofen were carried out with non-optimized heterogeneous fibers.

An additional important consideration about the Ibuprofen impregnation procedure is that, as a small pressure vessel is employed, both the pressurization and depressurization steps should be carried out slowly. On the one hand, if high-pressure rise rates are employed during the pressurization, the fibers could suffer damage due to a temperature increase (the pressurization process is almost adiabatic as the pressure rise is almost instantaneous with such small vessel) (**Figure S8**). On the other hand, a fast depressurization step could damage the thin fibers (which in this procedure are exposed and not imbibed into a PVOH film which also provides a higher mechanical strength).

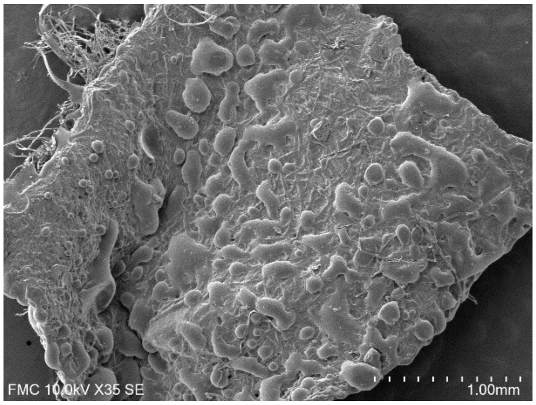


Figure S8. Hollow PCL fibers mat damaged (i.e., melt) due to the temperature increase during an Ibuprofen impregnation test carried out without controlling the pressure rise rate.

Finally, the Ibuprofen solubility on the PCL fibers was determined by TGA analysis. First, both Ibuprofen and PCL were analyzed separately from 50 to 400 °C with a heating rate of 5°C/min in N_2 atmosphere (**Figure S9.a** and **S9.b**). It was determined that the Ibuprofen degrades completely between 100 and 220 °C, while PCL starts to degrade a little bit over 220 °C. Therefore, in order to accurately determine the amount of Ibuprofen present on the loaded fibers, an isotherm of 2 hours at 220 °C was introduced in the TGA program, ensuring the complete degradation of Ibuprofen prior to the beginning of the PCL degradation (**Figure S9.c**).

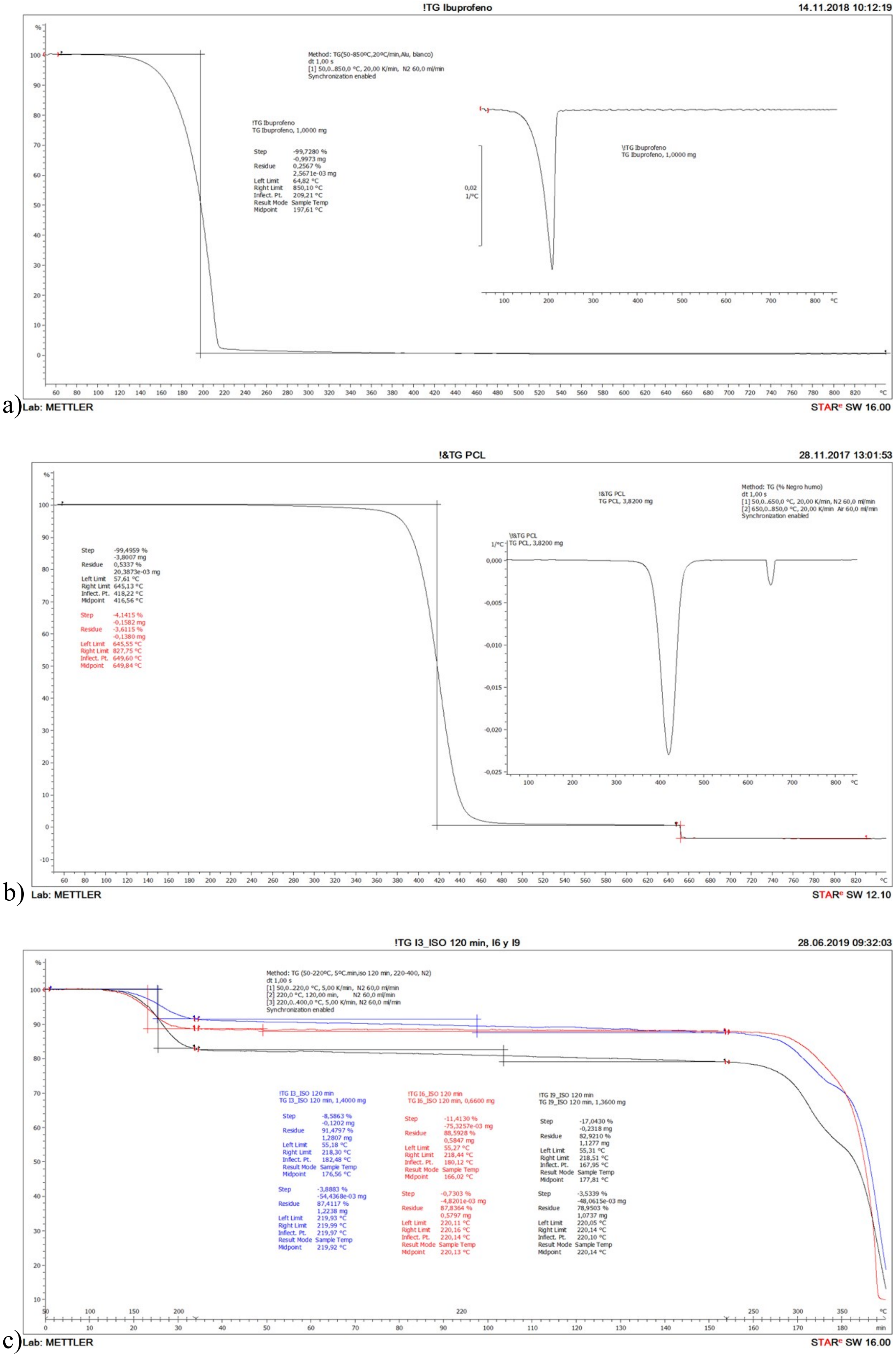


Figure S9. TGA results obtained for Ibuprofen (a), PCL (b), and diverse Ibuprofen-loaded PCL fibers evidencing the Ibuprofen weight loss during the isotherm (c).

S.I-5 DIFFERENTIAL SCANNING CALORIMETRY (DSC)

The melting point of both PCL and Ibuprofen was determined by DSC (see Experimental section), finding values about 61 and 77 °C, respectively (**Figure S10**). Then, the same procedure was applied on the obtained hollow fibers before and after the drug loading. It was found that the melting point of the PCL suffers no change with the foaming procedure (**Figure S10**). On the contrary, significant changes are found both for PCL and Ibuprofen on the drug-loaded fibers. The PCL melting temperature shows a slight decrease of about 1-2 °C, while the Ibuprofen melting temperature decreases up to 15 °C (**Figure S10**). These changes evidenced a significant interaction between the PCL and the Ibuprofen, with some Ibuprofen possible dispersed in a molecular form into the PCL (acting as a plasticizer and decreasing its melting point), and the rest forming small crystals, probably presenting defects due to the interaction with the PCL, leading to a 15 °C decrease of their melting point.[2–4] This is a desired feature on this kind of applications, as the Ibuprofen dispersed in molecular form or forming small crystals, instead of bigger ones, would present higher solubility in aqueous media without modifying their efficiency as medical drug.[4]

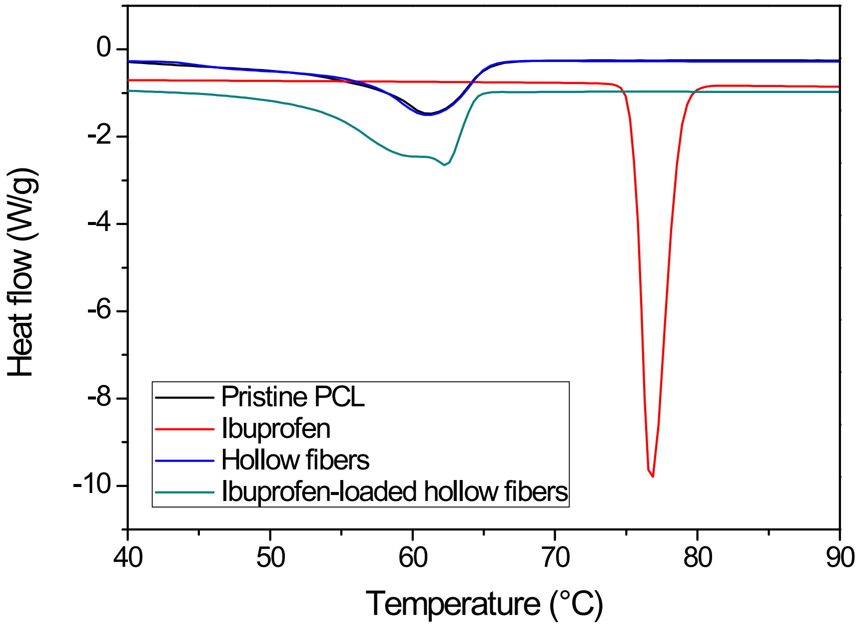


Figure S10. DSC results obtained for pristine PCL (black, coincident with the blue line), Ibuprofen (red), PCL hollow fibers (blue), and Ibuprofen (green)-loaded hollow fibers.

S.I-6 SCHEME OF THE PROPOSED FABRICATION PROCEDURE OF HOLLOW FIBERS

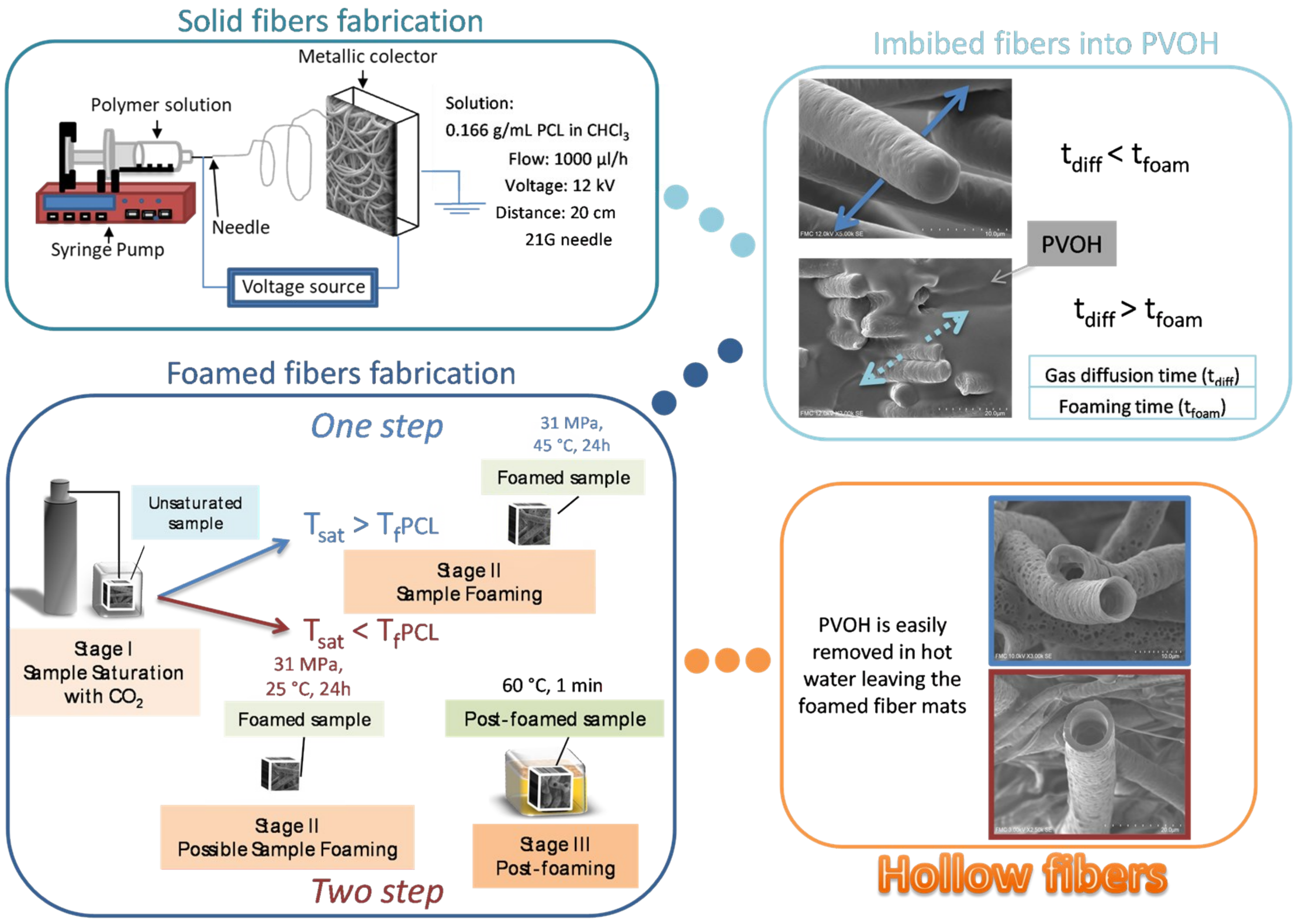


Figure S11. Scheme of the fabrication procedure developed to obtain polymeric hollow fibers from electrospun fibers by gas dissolution foaming processes.

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