Journal of Bioresources and Bioproducts 9 (2024) 486–494

Contents lists available at ScienceDirect

Journal of Bioresources and Bioproducts

journal homepage: https://www.keaipublishing.com/en/journals/journal-of-bioresources-and-bioproducts/

Research Article

Cavitation as a zero-waste circular economy process to convert citrus processing waste into biopolymers in high demand

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ARTICLE INFO

Keywords:
Cavitation
CytoCav
CytroCell
IntegroPectin
Green extraction

ABSTRACT

Cavitation in water only, no matter whether hydrodynamic or acoustic, is a zero-waste circular economy process to convert industrial citrus processing waste into high-performance polysaccharides in high demand in a single-step at room temperature and ambient pressure using a modest amount of electricity as the only energy input. Following previous reports in which we used hydrodynamic cavitation, we now use an industrial acoustic sonicator to demonstrate the general viability of cavitation to convert biowaste residue of the industrial squeezing of pigmented sweet orange (*Citrus sinensis*) into highly bioactive "IntegroPectin" pectin and micronized cellulose "CytroCell". From biomedicine through advanced composite membranes, said biomaterials hold great applicative potential. We conclude discussing the economic and technical feasibility of industrial implementation of the "CytroCav" process.

1. Introduction

Used since decades to produce pectin, the most valued food hydrocolloid (Seisun and Zalesny, 2021), citrus processing waste (CPW) obtained by the citrus juice industry in principle is ideally suited also as raw material for the production of microcrystalline cellulose (MCC) and of nanocellulose. Consisting of peels, seeds, pomace, and wastewater, this industrial agro-industrial waste (particularly when derived from orange fruits) is poor in lignin (< 2%) and rich in both cellulose and hemicellulose (Suri et al., 2022).

Commercially produced via acid hydrolysis using an excess of mineral acid at high temperature, the MCC is the excipient of choice in the pharmaceutical industry (Yohana Chaerunisaa et al., 2020). Its demand is expanding at quick rate because the MCC is increasingly used also in the food (as stabilizer, anti-caking agent, fat substitute, and emulsifier), beverage (as gelling agent, stabilizer and suspending agent) and cosmetic (as binder) industries (Trache et al., 2016). The high selling price of nanocellulose, on the other hand, so far has limited applications of this exceptional bionanomaterial to a few composite materials and, in the case of bacterial nanocellulose, in medicine (Ciriminna et al., 2024).

In a study devoted to "cavitation milling" of cellulose to nanofibrils Pinjari and Pandit (2010) were the first to report that cavitation bubbles produced either via hydrodynamic (HC) or acoustic (AC) cavitation applied to aqueous suspension of 63 μm MCC microparticles reduced the cellulose microparticle size nearly to the nanoscale. In detail, a 1% (*w/V*) suspension comprised of 0.5 kg MCC in 50 L water after HC afforded 1.36 μm microparticles, whereas AC was able to afford 0.3 μm cellulose particles. Furthermore, cavitation substantially reduced the crystallinity of the resulting micronized cellulose that went from 87% in MCC to 60% and 38% for

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https://doi.org/10.1016/j.jobab.2024.09.002

Available online 16 September 2024

HC and AC extracted fibrils, respectively. Water was the only reaction medium, and electricity the unique energy input employed to run the cavitation process making both cavitation-based extraction routes completely green. However, regardless of their remarkable large applicative potential, these results were nearly ignored by the cellulose and nanocellulose research community.

In 2021, we reported that the insoluble fraction of the HC-based extraction of lemon and grapefruit industrial processing waste performed directly on a semi-industrial scale (> 30 kg citrus biowaste in 120 L water) consists of cellulose of low crystallinity, high porosity, good water holding capacity and excellent dispersibility in water (Scurria et al., 2021a). We dubbed this new cellulose "CytroCell".

The subsequent year, along with Al Jitan et al. we reported that lemon CytroCell consists of 0.5–3.0 μm long cellulose microfibrils whose section varies between about 110 and 420 nm, organized in an open, mesoporous material of low crystallinity (0.33) and good water holding capacity (8 g water per g cell) (Al Jitan et al., 2022). On the other hand, grapefruit CytroCell consists of ramified microfibrils whose diameter varies from 500 nm to 1 μm. Readily dispersed in water, both CytroCell celluloses have large negative zeta-potential with zero charge point at pH 2.0 due to a substantial fraction of the cellulose cellobiose units being esterified with citric acid (Scurria et al., 2021a).

In any case, no pretreatment of the collected CPW was applied to inactivate enzymes, or remove the flavonoids, terpenes, and sugars residual in the industrial agro-waste; nor was mineral or organic acid added or the temperature raised to promote the extraction of the valued bioproducts, making the method particularly well suited for the joint production in a single-step of micronized cellulose and a newly extracted pectin rich in adsorbed flavonoids and terpenes named "IntegroPectin" (Meneguzzo et al., 2019).

The use of cavitation bubbles to improve pectin extraction from fruit peel goes back to 1986 when Kratchanov and co-workers in Bulgaria reported that extraction of pectin from apple pomace intensified by HC (Kratchanov et al., 1986) or intermittent AC (Panchev et al., 1988) significantly improved the extraction yield. Applications of AC to enhance pectin extraction from citrus peels had to wait the 2010s when Liu's team in China rediscovered Krachtanov's findings (Kratchanov et al., 1986). In 2014, the team reported that AC applied with heating (60 ˚C) to dried and pretreated grapefruit peel dispersed in acidic (pH 1.5) solution afforded enhanced yields of pectin (Xu et al., 2014). Furthermore, the extracted pectin had significantly higher swelling in water when compared to pectin conventionally extracted by hydrolysis in hot acidified water, with the pectin fibrils organized in a porous and much looser network. The team ascribed the enhanced extraction yield to disruption of the vegetal tissue driven by the cavitation bubbles. Three years later, the same scholars reported a two-stage process based on intermittent sonication to extract pectin from the same pretreated and dried grapefruit peel again in acidic (pH 1.5) aqueous (Wang et al., 2017). A second extraction of the AC-extracted biomaterial with water only at 70 ˚C was performed to dissolve the stagnant gel pectin layer formed around the swollen peel particle during the AC-based extraction. The process resulted not only in higher extraction yield, when compared to conventional heating extraction, but also in pectin of better quality being richer in rhamnogalacturonan-I (RG-I) regions. The team ascribed this finding to the much lower extraction time (and lower extraction temperature, 67 ˚C rather than 80 ˚C), and proposed a general mechanism for AC-assisted extraction of plant cell wall viscous polysaccharides (Wang et al., 2017).

Now, we use an industrial acoustic sonicator to demonstrate the general viability of cavitation to convert biowaste residue of the industrial squeezing of pigmented sweet orange (*Citrus sinensis*) into highly bioactive "IntegroPectin" pectin and micronized cellulose "CytroCell". From biomedicine (Ciriminna et al., 2021) through advanced composite membranes (Fontananova et al., 2024), said biomaterials hold great applicative potential. We conclude discussing the economic and technical feasibility of industrial implementation of the "CytroCav" process.

2. Materials and methods

Citrus processing waste resulting from industrial squeezing of red oranges organically grown in Sicily was generously donated by OPAC Campisi (Siracusa, Italy). Containing a relatively high amount of anthocyanins in both the rind and fruit pulp, the cultivars of said oranges are grown in a wide area around Mount Etna where the local climate conditions yield fruits imparted with unique color intensity and hue (Lo Piero, 2015). The CPW was packed in cardboard and placed in a low temperature chamber (4 ˚C) from which it was transported from the citrus processing plant in Syracuse, Sicily, to our Laboratories (distant more than 250 km) by a courier using a non-refrigerated van.

2.1. Materials preparation

A portion of a CPW sample stored in a freezer at –20 ˚C was brought to room temperature and used as raw material for the AC-assisted extraction. In brief, an aliquot (300 g) of CPW at room temperature was added with 3 L of ultrapure water (Barnstead Smart2Pure Water Purification System, Thermo Scientific) and homogenized with a domestic electric blender by grinding twice for 30 s at high speed each time.

The resulting mixture (Fig. 1) was extracted using the UIP2000hdT (20 kHz, 2 000 W) industrial sonicator (Hielscher Ultrasonics, Teltow, Germany) equipped with a hydraulic pump operating at 1.43 L/min. The extraction process was carried out in continuous flow-mode for 30 min at 50% of amplitude, in pulse condition (50 s on per 50 s off), setting the maximum work temperature at 50 ˚C. The power supplied to the digital probe-type sonicator was set at 800 W. A video of the extraction process during which the reactor is charged with the CPW dispersed in water can be freely accessed online (https://t.ly/B3EAc).

After extraction was complete, the mixture was filtered through a cotton cloth in order to separate the insoluble fraction from the aqueous phase. The aqueous phase was further filtered through a Büchner funnel by passing the mixture through a filter paper

Fig. 1. The aqueous mixture of red orange citrus processing waste (CPW) used for CytroCell and IntegroPectin extraction via acoustic cavitation.

Fig. 2. CytroCell cellulose paste (left) and in aqueous medium (right).

(Whatman, grade 589/3, retention < 2 μm) placed in the funnel. Pectin in the aqueous phase was isolated by freeze-drying using a FreeZone 4.5 Liter Benchtop Freeze Dry System (Labconco, Kansas City, MO, USA).

A portion (200 g) of the insoluble material was then mixed with 600 mL of ultrapure water and stirred at 500 r/min for 30 min using a KS 260 control flat shaker (IKA-Werke, Staufen, Germany).

The resulting material was further refined by pressing the resulting CytroCell cellulose paste through the mesh of a laboratory test sieve (Fig. 2, aperture of 300 μm, Cisa Sieving Technologies, Barcelona, Spain). Hence, the material was collected and centrifuged at 10 000 r/min for 10 min using an Allegra X-22R benchtop centrifuge (Beckman Coulter, Palo Alto, CA, USA). The material thereby obtained was washed twice with ultrapure water and lyophilized using the same freeze dryer mentioned above.

2.2. Zeta *(ζ)* potential and Fourier transform infrared *(*FT-IR*)* measurements

The ζ potential of red orange IntegroPectin and red orange CytroCell was measured using a Zetasizer Nano ZS analyzer (Malvern Panalytical, Malvern, Great Britain) assessing the electrophoretic mobility at 25 °C. Samples were prepared dispersing 5 mg of each dried material in 1 mL of ultrapure water.

The FT-IR spectra were recorded using a FT-IR spectrometer (Bruker, Billerica, MA, USA) spanning the 4 000–400 cm^{-1} range, with a lateral resolution of 2 cm^{-1} and 128 scans. Approximately, 1 mg of lyophilized IntegroPectin or CytroCell biomaterial was added to 100 mg of ultrapure KBr (FT-IR grade, ≥ 99% pure, Sigma-Aldrich) in a mortar. The resulting mixture was pressed using a pestle to form a homogenous powder. Subsequently, a Specac Mini-Pellet laboratory hydraulic press was employed applying 12 t weight for 5 min to prepare the pellets required for the spectroscopic analysis.

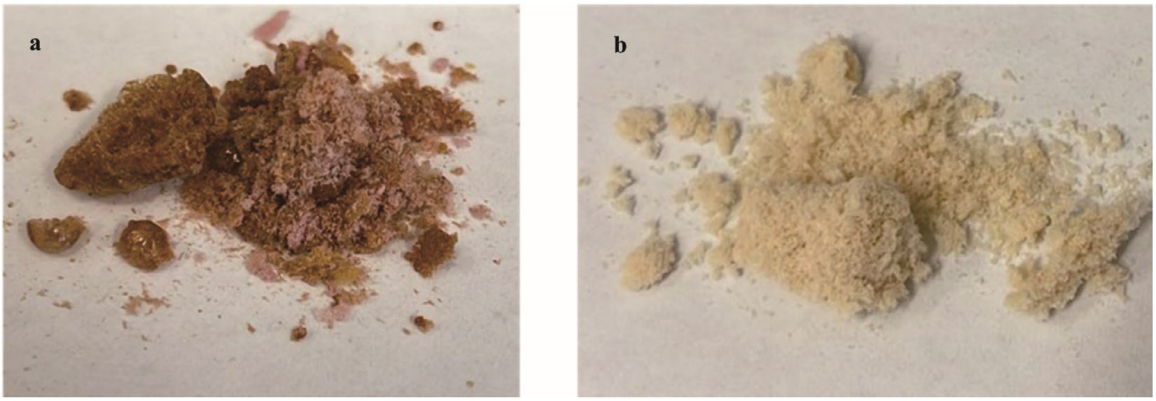

Fig. 3. Lyophilized red orange IntegroPectin (a) and CytroCell (b) extracted via acoustic cavitation.

2.3. X-ray diffraction analysis (XRD)

The XRD analyses were performed using a D5005 X-ray diffractometer (Bruker AXS, Karlsruhe, Germany) operating at 40 kV and 30 mA to obtain the diffraction profile at 0.15°/min acquisition rate over a 5.0°–40.0° of 2θ range. The X-ray radiation was generated via a copper (K_α) anode and made monochromatic via the instrument's secondary monochromator. A portion of CPW sample stored at –20 °C was brought to room temperature and used as raw material for the AC-assisted extraction.

2.4. TEM and FE-SEM analysis

The scanning transmission electron microscopy (STEM) samples of red orange CytroCell were prepared by suspending a small amount of powder in distilled water, treating in an ultrasonic bath and drop casting them on carbon film supported 200-mesh copper grids. All samples were dried at room temperature before analysis. The samples were then mounted on a grid and analyzed by using a Tescan MAGNA ultra-high resolution field emission scanning electron microscope (UHR FE-SEM) equipped with a STEM detector. The STEM analysis was performed in bright field and at an accelerating voltage of 30 keV. Samples for FE-SEM analysis were prepared by applying the water dispersions on silicon substrates and drying at room temperature. They were coated with a few nanometers of a conductive graphite layer. The FE-SEM images were recorded with a Zeiss high-spatial-resolution LEO Gemini 1530 field emission scanning electron microscope (FE-SEM). Images were all recorded in the secondary electron Inlens mode at an acceleration voltage of 10 keV.

2.5. Data processing

The experimental data and graph were processed using the version 2024 of the Origin(Pro) software (OriginLab, Northampton, MA, USA).

3. Results and analyses

Fig. 3 shows that the CytroCell and IntegroPectin biomaterials extracted via acoustic cavitation and freeze-dried are both free flowing powder. The difference in color between the pectin and cellulose based materials is due to the water-soluble anthocyanins abundant in pigmented red orange that, following solubilization in the aqueous phase along with water-soluble pectin, end up adsorbed and concentrated at the outer surface of the IntegroPectin pectin open and loose polymeric structure acting as a "molecular sponge" (Scurria et al., 2021b).

Cavitation results in the enhanced solubilization also of these poorly soluble and highly bioactive flavonoids likely due to emulsion formation during extraction (Piacenza et al., 2022). Poorly soluble biophenols abundant in red orange peel and fruit such as *p*-coumaric, hesperidin and naringin (Legua et al., 2022) are adsorbed also at the surface of the poorly crystalline and similarly loose and open structure of CytroCell cellulose. Subsequent computational studies suggest that flavonoids are partly chemically bound to the pectin polymeric chain (Butera et al., 2024).

Amounting to (–22.6 ± 3.95) mV the ζ potential of AC-extracted red orange IntegroPectin is 4.6 mV higher, in absolute value, than that of red orange CytroCell (–18 ± 7.03 mV). Likewise to the case of lemon IntegroPectin obtained via HC (Nuzzo et al., 2020), we ascribe this difference to the presence of both anionic carboxylate groups typical of pectin galacturonic acid moieties as well as of citrate groups formed by esterification with free citric acid abundant in CPW (Clements, 1964) taking place at the interface of the imploding cavitation bubbles. Said high values of the ζ potential are important because guidelines classifying colloidal dispersions with ζ potential values of 20–30 mV and $^{>}$ ± 30 mV point to moderately stable and highly stable dispersions, even though certain colloids with low ζ potential can also be stable (Bhattacharjee, 2016). This enables application of both IntegroPectin and CytroCell

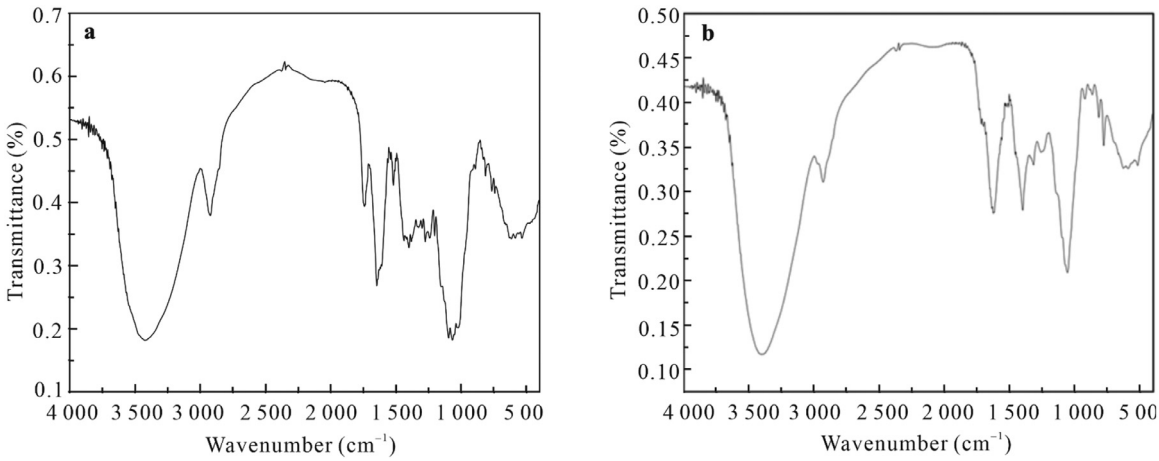

Fig. 4. Fourier transform infrared (FT IR) spectrum of red orange CytroCell (a) and red orange IntegroPectin (b) obtained via acoustic cavitation.

dissolved or dispersed in water as stabilizers of colloidal suspensions. Low-methoxy pectin citrus pectin is widely used in the food industry as key stabilizer ingredient in low-fat commercial yoghurts improving firmness, sensory-liking attributes and rheological parameters (Kubber et al., 2021).

The FT-IR spectrum of red orange CytroCell obtained via AC (Fig. 4a) is similar to that of lemon CytroCell obtained via HC (Scurria et al., 2021a), showing all the main signals of cellulose with moisture content (Cichosz and Masek, 2020). The broad peak centered at 3 423 cm^{-1} is typical of O–H bonds stretching vibrations of both free and bound water, as well as the O–H bonds of hydroxyl groups in the cellulose cellobiose units. The band at 2 923 cm^{-1} corresponds to the stretching vibrations of C–H in the saturated carbon rings of polysaccharides. Likewise to lemon CytroCell obtained via HC, the sharp peaks at 1 742 and 1 648 cm^{-1} are the stretching signals of the free and esterified carboxylic groups of citric acid in cellulose citrate formed as a result of the esterification reaction between the primary alcohol group of cellulose and the residual citric acid present in CPW. Peaks in the fingerprint region are also distinctive of cellulose. The signal at 1 400 cm^{-1} is due to the bending of CH_2 groups in the pyranose ring, whereas peak at 1 242 cm^{-1} originates from bending vibration of the C–OH groups at C–6. The peaks at 1 160 and 1 100 cm^{-1} correspond to the stretching vibration of the C–O–C β-(1-4)-glycosidic bond, and to the stretching vibrations of C–O bonds in saturated six-membered rings, respectively. Finally, the signal at 897 cm^{-1} is due to stretching vibrations of C–O–C at the same glycosidic linkage from the amorphous region of cellulose.

The FT-IR spectrum of red orange IntegroPectin (Fig. 4b) is similarly close to the analogous spectrum of lemon pectin obtained via HC (Nuzzo et al., 2021a). The broad band centered at 3 406 cm^{-1} is due to the O–H stretching vibration of the pyranose ring and adsorbed water. However, this band is significantly less pronounced in commercial citrus pectin (not shown), thus indirectly pointing also in the case of this IntegroPectin obtained via AC to the presence flavonoids and hydroxycinnamic acids especially abundant in the citrus fruit peel. In this case, the latter flavonoids consist of both water-soluble anthocyanins (Lo Piero, 2015), as well as of other biophenols abundant in red orange such as *p*-coumaric, hesperidin and naringin (Legua et al., 2022). Evidence of the presence of said biophenols stems from the numerous large peaks in the 1 599–1 594 cm^{-1} region typical of aromatic molecule skeleton vibrations, including ν(C=C) and ν(C=O) of the aromatic skeleton and keto groups (Ricci et al., 2015; Krysa et al., 2022). The lower absorption signal at 2 931 cm^{-1} is due to the stretching vibrations of C–H bonds of CH and CH_2 groups of polysaccharide rings. The strong signal at 1 625 cm^{-1} is attributed to the asymmetric stretching of the carboxylate groups of pectin homogalacturonan (HG) chain. This large peak overlaps with the characteristic stretching vibrations of methyl esterified carboxyl groups (1 760–1 730 cm^{-1}) usually observed in commercial citrus pectin.

The XRD spectra (Fig. 5) for red orange IntegroPectin and red orange CytroCell obtained via AC confirm that CytroCell consists of cellulose and that IntegroPectin is an amorphous pectin polymer. In contrast to commercial citrus pectin (showing many diffraction peaks characteristic between 12.4° and 40.2° due to partly crystalline arrangement of the HG chains (Panwar et al., 2023)), pectin sourced via AC from fresh red orange CPW shows (Fig. 5a) a broad peak centered around 18.5° pointing to complete decrystallization of the HG regions, as it happens for lemon (Nuzzo et al., 2022) and grapefruit IntegroPectin obtained via hydrodynamic cavitation (Nuzzo et al., 2021b). In both cases cavitation destroys the “fringed-micellar” structure of the crystalline regions of the semicrystalline pectin biopolymer (Gohil, 2011).

Said enhanced amorphousness, along with the retained RG-I regions and low degree of esterification with methoxy groups, also explains the significantly larger solubility of the IntegroPectin in water at room temperature when compared to the poorly soluble commercial citrus pectin that requires prolonged heating and sonication to dissolve in water, adding further applicative value to the IntegroPectin when compared to conventional citrus pectin extracted via acid hydrolysis in hot water.

The XRD spectrum of red orange CytroCell in Fig. 5b shows the characteristic diffraction peaks of cellulose with the 16.4° peak (101 plane), with the amorphous region between 16.4° and 18.0°, and the highest peak of the 002 lattice diffraction above 21° corresponding to diffraction from the 002 plane (Yao et al., 2020). Accurate determination of the crystallinity index (CI) of this

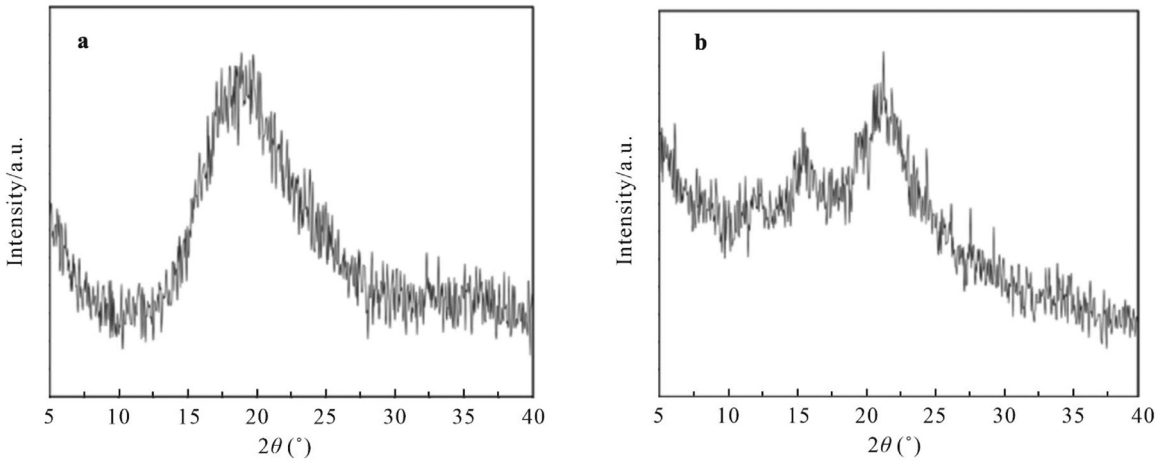

Fig. 5. X-ray diffraction analysis (XRD) spectra of red orange IntegroPectin (a) and red orange CytroCell (b) obtained via acoustic cavitation.

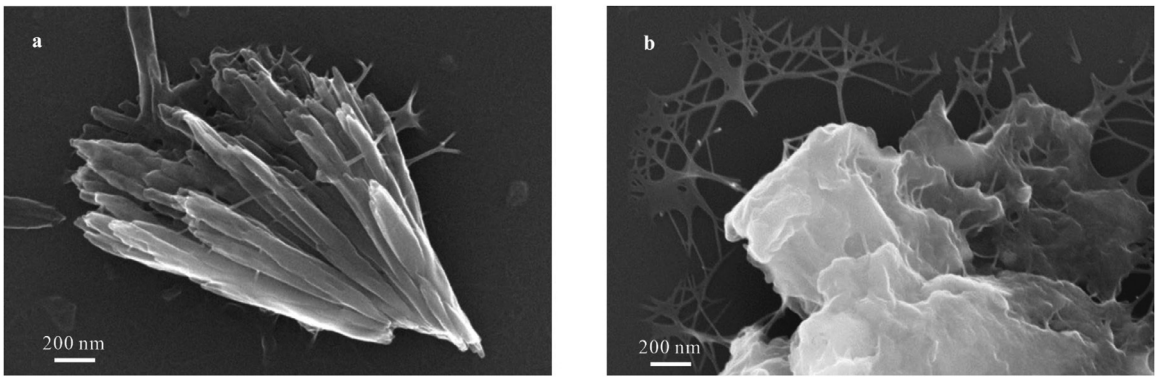

Fig. 6. Field emission scanning electron microscopy (FE-SEM) image (a), and scanning transmission electron microscopy (STEM) image (b) of red orange CytroCell obtained via acoustic cavitation.

and other CytroCell samples derived from other citrus fruits is ongoing. In general, in acoustic cavitation the rate of dissipation of the energy generated by the imploding cavitation bubbles is higher than what happens during HC due to more intense cavitational collapse and absence of fluid flow (Pandit et al., 2021). The enhanced energy dissipation increases disruption of the crystalline order in regions of the aggregated cellulose nanofibrils. Accordingly, AC of MCC results in cellulose having CI much lower (0.38) than MCC undergoing HC (0.60) (Pinjari and Pandit, 2010).

The electron microscopy images experiments confirm that AC micronizes the cellulose fibrils of red orange processing waste in submicron cellulose rods, similar to those observed in lemon CytroCell obtained via HC (Al Jitan et al., 2022). The field emission scanning electron microscopy (FE-SEM) image of CytroCell in Fig. 6a shows the presence of microfibers with nanorod-like morphology. A ramified structure around the nanorods is also clearly visible.

The scanning transmission electron microscopy (STEM) image in Fig. 6b shows further evidence that red orange CytroCell is mainly composed of elongated microfibers with a rod-like structure, according to FE-SEM images. A length of about 0.5–1.0 μm and a section of about 0.1–0.2 μm (100–200 nm) is observed. This new CytroCell extracted via AC, in other words, from a morphology viewpoint is very similar to lemon CytroCell obtained via HC (Al Jitan et al., 2022), being mainly composed of elongated microfibers with a rod-like structure. The main difference concerns the crystallinity index, that in the case of the AC-extracted citrus CytroCell is nearly half of the HC-extracted CytroCell.

The outcomes of applying acoustic cavitation to fresh (untreated) citrus processing waste obtained from the industrial production of pigmented sweet orange juice, demonstrate that cavitation is a general circular economy route to “CytroCell” micronized cellulose, and “IntegroPectin” pectic polymer rich in negatively charged carboxylates and in adsorbed flavonoids. These new biopolymers, so far chiefly obtained via hydrodynamic cavitation, have remarkable properties described in numerous studies. For example, CytroCell derived via HC from lemon waste is soluble in the aprotic dipolar solvent Cyrene, and is readily dispersed in water so that it can be used to functionalize and enhance the mechanical and chemical stability of anion exchange membrane comprised of a polymerizable ionic liquid (Fontananova et al., 2024). Similarly, numerous *in vitro* and *in vivo* studies published since 2020 report the cardioprotective, anti-inflammatory, mitoprotective, neuroprotective, anticarcinogenic, antimicrobial, and antioxidant properties of both lemon and grapefruit IntegroPectin obtained via HC.

As mentioned above, using cavitation as green extraction process, no expensive pretreatments of fresh CPW are needed such as prolonged heating of CPW in water at 90 °C to deactivate enzymes (Wang et al., 2017), or expensive drying of citrus processing biowaste containing 80% (*w*) water (Satari and Karimi, 2018).

In brief, the findings reported in this study further demonstrate that chemical sciences (chemistry and chemical engineering) can contribute to ending poverty, improving health and preserving the natural environment when applied to the valorization of citrus processing waste, an agro-industrial biowaste produced at the rate of over 10 million tons per year (Suri et al., 2022). The CPW is characterized by uniquely high organic matter content (95% of total solids) and high water content, and is an excellent source of cellulose and pectin, provided that no expensive drying is required. For example, the high cost of drying CPW by burning natural gas or other fuels to supply pectin manufacturers with dried CPW, actually leads most citrus industry companies to dispose of CPW mostly as cattle feed.

No harmful waste is generated in the process, and no heating is needed, resulting in substantial savings on the amount of energy (electricity and heat) used in conventional pectin and nanocellulose production processes. Furthermore, the capital expenditure (CapEx) and the footprint of both hydrodynamic and ultrasound cavitation reactors are a small fraction of those of conventional pectin and cellulose conventional extraction plants.

4. Discussion and conclusions

Cavitation enables the realization of the long-researched citrus biorefinery (Pfaltzgraff et al., 2013), relying on a single, easily scalable and completely green technology allowing direct treatment of fresh CPW at citrus processing plants to produce two highly valued biopolymers that will shortly find multiple practical applications. This further justifies the uptake of cavitation run in water only (the “CytroCav” process) for the extraction of pectin, cellulose, flavonoids and terpenes from citrus processing waste in place of old chemical extraction technologies relying on organic solvent, mineral acid, and large amounts of energy (heat and electricity).

Meeting the principles of green extraction (Chemat et al., 2012), the process requires few practical steps for the transition from the lab to large-scale industrial implementation both when extraction will be carried out by hydrodynamic or by acoustic cavitation. The HC-based extraction of CPW in water only was first demonstrated in 2019, when we reported the extraction of 30 kg of orange industrial processing waste performed in 120 L water, namely directly on semi-industrial scale (Meneguzzo et al., 2019). The subsequent year, we showed that the overall process for a HC-based extraction plant with a nominal capacity of about 2 000 L undertaking the processing of 500 kg waste citrus peel in 1 500 L water in just 2 h would only require three new plant components besides the industrial scale cavitation-based extractor: a grinder, a filter/separator, and a continuous freeze-dryer (Meneguzzo et al., 2020). Similar highly efficient freeze dryers today are commonly operated at advanced fine chemical and pharmaceutical companies (Capozzi et al., 2019).

Getting to AC-based extraction, industrial plants already exist using commercial high-frequency wave acoustic generators (horns or bath systems) for the extraction of natural products (Chemat et al., 2017). Specifically one new plant aimed at the extraction of numerous natural products starting from citrus pectin relying on acoustic cavitation recently started to operate in Israel aiming to produce 1 000 t of pectin (and 3 000 t of cellulose sold as “dietary fiber” to bakery, dairy and meat industries) yearly from dried lemon CPW yearly (https://pulvit.com). Presenting the industrial plant, the company notes how the investment required for a pectin plant having similar capacity using conventional extraction using mineral acid followed by vacuum evaporation and alcohol precipitation (VEAP) would exceed $25 million (https://pulvit.com).

The conventional pectin production and purification process relying on acid hydrolysis and VEAP furthermore has significant safety risk due to the employment of flammable alcohol generating explosive vapors in the vacuum installation used to recover the expensive alcohol (Muhidinov et al., 2021). Finally, as mentioned above integration of cavitation-based extraction of IntegroPectin and CytroCell into existing citrus fruit processing industrial facilities, eliminates the need of expensive drying of citrus processing waste needed to end quick biological degradation of said waste. Occupying small room space due to small size (1–3 m^3) of the industrial AC-based and HC-based extractors, an extraction plant relying on the CytroCav process carried out in water only does not require any effluent treatment plant, being easily and rapidly installed at the aforementioned agrifood industry plants present in all *Citrus* growing countries. A study discussing production costs, savings, and market opportunities for both IntegroPectin and CytroCell production will follow in due time.

Availability of data

Data available on request from the corresponding authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rosaria Ciriminna: Conceptualization, Supervision, Writing – review & editing, Resources, Methodology. **Giuseppe Angellotti:** Formal analysis, Investigation, Software. **Giovanna Li Petri:** Formal analysis, Investigation, Software. **Francesco Meneguzzo:** Con-

ceptualization, Resources, Methodology. **Cristina Riccucci:** Formal analysis, Investigation, Software. **Gabriella Di Carlo:** Formal analysis, Investigation, Methodology. **Mario Pagliaro:** Conceptualization, Writing – original draft, Methodology, Supervision.

Acknowledgments

This article is dedicated to Professor James H. Clark, University of York, for all he has done to advance green chemistry and the bioeconomy. Thanks to OPAC Campisi (Siracusa, Italy) for kindly providing the red orange processing waste. Work of G.L.P. was supported by European Union NextGenerationEU (PNRR-Mission 4 Component 2, Investment 1.3 - D.D.1551.11-10-2022, PE00000004) within the MICS (Made in Italy-Circular and Sustainable) Extended Partnership. Work of G.A. was supported by European Union NextGenerationEU (PNRR-Mission 4 Component 2-Investment 1.5 (ECS00000022)-CUPB63C22000620005) within the SAMOTHRACE (Sicilian Micro and Nano TechnologyResearch and Innovation Center) Innovation Ecosystem. We thank Ministero dell'Università e della Ricerca for funding, Progetto "FutuRaw", Le materie prime del futuro da fonti non-critiche, residuali e rinnovabili, Fondo Ordinario Enti di Ricerca 2022, CNR (CUP B53C23008390005).

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