**Process Intensification *via* Continuous and Simultaneous Isolation of Antioxidants:
An Upcycling Approach for Olive Leaf Waste**

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Abstract

Isolation of individual pharmaceutical-grade bioactive compounds from complex plant extracts is still a sustainability challenge. Process intensification improves manufacturing design to achieve significant benefits in process efficiency and operation, product quality, and waste management. A process optimization and intensification methodology for the simultaneous isolation of biophenols from agricultural waste using imprinted materials and nanofiltration membranes is reported herein. First, temperature-swing molecular imprinting technology was used to selectively extract individual biophenols from olive leaf extracts. Second, solvent-resistant nanofiltration was used to *in line* concentrate the product and waste streams as well as recover the solvent. The predictive mathematical models for the adsorption dynamics and the membrane separation resulted in a significant reduction in the carbon footprint, *E* factor and economic sustainability. The process was designed for easy operation with multi-way valves to aid safety and reduce operating costs. The presented process intensification methodology can be generally exploited for waste upcycling through sustainable isolation of multiple high-value products from complex mixtures.

Introduction

Sustainable manufacturing of fine chemicals is one of the main goals of the 21st century. The agricultural and industrial sectors are responsible for 57% of the greenhouse gas emissions contributing to climate change.¹ There are aspirations to enable scientists and engineers to move towards more sustainable design and development of chemical processes used in the manufacture of pharmaceutical ingredients.^{2,3,4} Pharmaceutical, personal care, food and nutritional industries extract natural compounds from a range of plants and animals. In particular, there is an increasing interest in developing processes for the extraction of biophenols with diverse examples such as column chromatography,⁵ centrifugal partition chromatography,⁶ superheated liquid extraction,⁷ pressure drop texturing,⁸ reduced-pressure boiling extraction,⁹ ultrasound- and microwave-assisted extraction,^{10,11} and membrane processes.¹²

Conventional downstream separation processes are often unsustainable due to their high share of total manufacturing costs and industrial energy usage.¹³ Through innovative approaches, process intensification aims to reduce the environmental burden and operating expenditures, while increase process efficacy, product quality, and reusability.¹⁴ Continuous processes^{15,16} and membrane-based separations¹⁷ can significantly improve the sustainability

and economics of chemical manufacturing.¹⁸ The field of organic solvent nanofiltration (OSN) has significantly evolved in the past decade, and robust membranes are available for *in line* solvent recycling, which can drastically reduce solvent consumption.^{19,20,21} OSN has recently been proposed for the fractionation of lignin,²² flavonoids²³ and polyphenol²⁴ compounds. However, the obtained fractions contained a mixture or structurally similar compounds with similar molecular weight. Conventional olive leaf extractions result in a blend of polyphenols, and the isolation of individual compounds is yet to be developed.^{25,26} The reported methodologies use undesirable solvents (e.g. benzene, dichloromethane, diethyl ether) and their multicomponent mixtures, considerably basic or acidic conditions, and process steps at low (0 °C) or high (60 °C) temperature.^{5,27} Ethyl acetate was selected for this work because it is ranked as a green solvent in the GSK solvent selection guide.^{2,3} Note that the use of ethyl acetate in food and flavors depends on the country.

In our previous work, the synergistic coupling of imprinted materials with membrane-based separations was found to be an efficient process intensification tool for the isolation of high-purity oleuropein (OR).²¹ Concurrently, molecular imprinting has also been maturing into a robust and selective separation technology suitable for downstream processing.^{28,29} Biophenols occur in olive leaves, which are treated as agricultural waste after fruit harvest, although these compounds can be turned into high-value products.³⁰ The beneficial properties of biophenols, in particular oleuropein, has been extensively studied.³¹ Besides its direct pharmacological use, oleuropein can be converted into various high-value compounds.³² Besides oleuropein other pharmaceutically important biophenols, particularly luteolin (LU) and pinoresinol (PN), can be found in olive leaves.

The present study demonstrates development and optimization of a continuous and simultaneous isolation process for three biophenols based on temperature-swing adsorption (Figure 1). The product and waste streams were concentrated, the solvent was *in line* recycled, and their effect on the *E* factor, carbon footprint and economic sustainability of the process was investigated. The application of the hybrid process consisting of imprinting technology and nanofiltration can be extended to the isolation of other natural compounds from complex mixtures.

Figure 1. Schematic piping and instrumentation diagram for the continuous and simultaneous isolation and fractionation of oleuropein (OR), luteolin (LU) and pinoreosinol (PN) from olive leaf extracts. The two sets of three columns are equipped with imprinted materials selective to OR (1), LU (2) and PN (3). Both the waste and biophenol streams are concentrated by the membrane units, while the ethyl acetate is *in line* recycled.

Materials and methods

General

Reagents (reagent grade), solvents (analytical grade) and oleuropein, luteolin and pinoresinol standards were purchased from Sigma-Aldrich. The porogen acetonitrile was dried over 4 Å molecular sieve. Millipore Type II water was employed for the membrane preparation. ^1H and ^{13}C NMR spectra were recorded on a Bruker AV-400 spectrometer. A VWR-Hitachi Chromaster DAD-HPLC equipment was employed for the analysis of the target compounds. ACE 5 μm , 100 Å, C18 column with 150×4.6 mm dimensions was used for the chromatographic separation, and the flow rate of the eluent was set at 1 mL min^{-1} .²¹ The volume of injection was 15 μL . Acetonitrile and Millipore Type I water containing 0.1% trifluoroacetic acid were used as eluents in channel A and B, respectively. The gradient was linear from 10 to 90% A in 60 min, followed by 90% A hold for another 5 min. At the end of the method a re-equilibration period was set for 15 min. The temperature of the column housing was set at 25 °C. Mass spectrometry measurements were performed using a triple quadrupole mass spectrometer with positive electrospray ionisation source coupled to an Agilent 1100 HPLC equipment.

Imprinted materials

The fabrication of the imprinted materials was performed according to our previous procedure.²¹ 2 mmol of 1-(4-vinylphenyl)-3-(3,5-bis(trifluoromethyl)phenyl)urea, 1 mmol styrene functional monomers, 1 mmol biophenol as template, 15 mmol ethylene glycol dimethacrylate crosslinker, 0.1 wt% recrystallized 2,2'-azobis(2-methylpropionitrile) radical initiator, 75 mg perfluoro polymeric surfactant emulsifier, 60 mL perfluoro methylcyclohexane dispersing phase, and 15 mL solvent (porogen: acetonitrile) were mixed and vigorously stirred for 15 min under Nitrogen. The photopolymerization was performed over 6 hours by 365 nm irradiation with UV light under inert atmosphere. The obtained microbeads were washed with ethanol to remove any residual, unreacted components, and the template. The materials were dried in vacuo over a day at room temperature. Preparative chromatography columns (1), (2) and (3) with 250 mm length and 10 mm inner diameter were wet-loaded with approximately 8 grams of OR, LU and PN imprinted polymers, respectively.

Kinetic and adsorption isotherms

10 mL of standard solutions of OR, LU and PN were prepared at 1 g L⁻¹ concentration in ethyl acetate, which were loaded on 5, 15, 25, 50, 100, 150 and 200 mg polymers. The vessel was sealed and agitated for 24 h at 25 °C, 35 °C and 45 °C, and 300 rpm in an incubator shaker. For the quantification of the biophenols, the supernatants were analyzed by HPLC with 0.2, 0.4, 1, 1.5, 2, 3, 5, 8, 12 and 24 h intervals.

Assessment of membrane separation

Biophenols in ethyl acetate at 1 g L⁻¹ concentration were filtered under 35–45 bar pressure employing a cross-flow nanofiltration rig equipped with 52 cm² polymer membranes. Solvent-resistant, polybenzimidazole-based membranes were used (refer to Section 8 and 9 of the Supporting Information). The permeance value of the nanofiltration membranes was determined by dividing the solvent flux with the applied pressure. On the other hand, the biophenol rejection (R , Eq. 1) were derived by measuring their permeate concentration (C_{perm}), and calculating the ratio of the molecules retained by the membrane (C_{ret}). Three independent experiments were performed, and the average data and their standard deviations are reported in Figure S6 in the Supporting Information.

$$R = 1 - \frac{C_{perm}}{C_{ret}} \quad \text{Eq. 1}$$

Continuous separation

The schematic of the piping and instrumentation diagram is shown in Figure 1. The feed concentrations for OR, LU and PN in the olive leaf extract were 0.966, 1.042 and 0.311 g L⁻¹, respectively. The feed stream (Q_f) is transferred at 2 mL min⁻¹ flow rate from the storage vessel to Column Housing A set at 25 °C for the adsorption of OR, LU and PN in Columns 1A, 2A and 3A, respectively. The adsorption utilizes Valves 1, 2 and 3 in position 1 allowing the extract to flow through Columns 3A, 2A and 1A, followed by the concentration of the waste stream leaving Column 1A diverted into the nanofiltration unit (NF1) through Valve 4 in position 1. The membrane area and the total volumetric flow rate (α , Eq. 2) was 104 cm² and 2.5% for all nanofiltration units. The solvent is recycled as the permeate stream at a flow rate of 1.95 mL min⁻¹, while the retentate is collected as a concentrated waste stream at a flow rate of 0.05 mL min⁻¹ (Q_{ret}).

$$\alpha = \frac{Q_{ret}}{Q_f} \quad \text{Eq. 2}$$

Simultaneously, ethyl acetate solvent is transferred at 2 mL min⁻¹ flow rate from a storage vessel to Column Housing B set at 46 °C for the desorption of OR, LU and PN from Columns 1B, 2B and 3B, respectively. The adsorption utilizes Valves 1, 2 and 3 in position 1 allowing the desorbed and pure OR, LU and PN streams to be transferred into their individual nanofiltration units (NF2, NF3 and NF4, respectively) through Valve 4 in position 1. The solvent is recycled as the permeate stream at a flow rate of 1.95 mL min⁻¹, while the retentate is collected as a concentrated product stream at a flow rate of 0.05 mL min⁻¹.

The temperature-swing adsorption is realized by switching Valves 5 and 6 of the thermostats to keep allow adsorption and desorption to take place in Colum Housing A and B at 25 °C and 46 °C, respectively. In valve position 1, Column Housings A and B are used for adsorption and desorption, respectively. In valve position 2, Column Housings B and A are used for adsorption and desorption, respectively.

Results and discussion

Adsorption thermodynamics

A numerical model of the adsorption process has been developed to simulate the separation of the three biophenols under different conditions. Thermodynamic data of adsorption required in the model has been obtained experimentally and can be found in Figure 2. Fitting expressions have been obtained from the experimental points to relate q_{eq} vs. C in equilibrium at different temperatures (25 °C, 35 °C, 45 °C). Further details on the adsorption isotherm analysis can be found in Section 4 of the Supporting Information.

Figure 2. Adsorption isotherms at different temperatures for the different biophenols: a) OR, b) LU and c) PN, respectively. C_f^i and C_a^i are the free and adsorbed concentrations of compound i . The symbols indicate experimental data points, while the curves are predicted based on modelling presented on Section 4 of the Supporting Information.

In addition to the equilibrium thermodynamic data, the kinetics of adsorption have also been determined experimentally. This information has been used to estimate an effective intraparticle mass diffusivity required by the mathematical model of the columns. Figure 3 shows the experimental results obtained for the time evolution of the concentration of each biophenol in solution versus the amount absorbed and the corresponding fitted expressions. Values of $D_{\text{eff}} = 1.07 \times 10^{-14} \text{ m}^2 \text{ s}^{-1}$ ($R^2 = 0.983$), $D_{\text{eff}} = 1.13 \times 10^{-14} \text{ m}^2 \text{ s}^{-1}$ ($R^2 = 0.980$), $D_{\text{eff}} = 0.40 \times 10^{-14}$

$^{14} \text{ m}^2 \text{ s}^{-1}$ ($R^2 = 0.995$) have been obtained from non-linear regression for oleuropein, luteolin and pinoresinol, respectively. Section 6 of the Supporting Information presents further details on the evaluation of the effective intra-particle diffusivity from the experiments.

Figure 3. Kinetic data for the adsorbents for the estimation of the intra-particle effective diffusivity for OR, LU, and PN. c_f^i and c_a^i are the free and adsorbed concentrations of compound i .

Column description

The developed model of the adsorption separation process was used to simulate the system behaviour under different conditions, such as the effect of feed flow on the column outlet concentration ($C_o(t)$), the exploitation rate of the column capacity, and the loss of biophenols. Figure 4 shows the breakthrough curves for the different biophenols as a function of processed volume of olive leaf extract, which have been validated with experimental data for a flow rate of 2 mL min^{-1} . Section 3 of the Supporting Information presents further details on the mathematical framework and assumptions. The main goal of the simulations was to define optimised injection times that minimise losses of biophenols but that maintain high column productivity rates (Figures 5 and 6.).

Figure 4. Optimization processing rates: breakthrough curves of a) OR, b) LU and c) PN ($C_o(t)$) as a function of processed volume of olive leaf extract.

After validation, the mathematical model of the column was used to study the effect of the flow rate and the injection time on the process (refer to Section 7 in the Supporting Information). It has been observed that, as the inlet flow rate is increased, less residence time is given for biophenol molecules to adsorb until equilibrium is reached (Figure 4). At fixed flow rate values, an increase in the length of the injection time reduces the productivity with reducing the processed mass and leads to increasing biophenol waste.

Figure 5. The effect of injection time on the normalized processed mass and the normalized mass loss of a) OR, b) LU, and c) PN at three different flow rates.

Figure 6. Mass loss (*) and processed mass (#) as a function of normalized processed mass of a) OR, b) LU, and c) PN.

The mathematical model was further used to determine desorption temperature that grants equal adsorption and desorption times. This was done in order to simplify the process control and operation and minimize energy consumption. The simulations have shown that 46 °C is the minimum temperature that ensures 99% recovery for all the biophenols in equal adsorption and desorption time (Figure 7a). This value was used for calculating the biophenol recoveries and the green metrics analysis.

Figure 7. a) The effect of the desorption temperature on the concentration of the components at the outlet of the column ($C_o(t)$) at 2 mL min⁻¹ flow rate; b) Concentration profile for the continuous process at 46 °C desorption temperature and 2 mL min⁻¹ flow rate: dynamics of biophenol concentrations at the outlet of the columns; c) The effect of column selectivity (γ , Eq. S13) on the purity in the outlet for the three components.

The selection of equal temperatures for the adsorption and desorption stages for all the biophenols offers easier control. Moreover, swapping between the columns can be done by simultaneously switching the six- and four-way valves after each cycle and allows the use of only two thermostats (see Figure 1). Minimizing the number of thermostats is crucial to achieve a sustainable operation.²¹ The outlet concentration profile for the hybrid process configuration with two sets of columns coupled with an *in line* solvent recycle step has been predicted with numerical calculations in a continuous mode up to 4 cycles (Figure 7b), 9.6 g, 13.3 g and 2.6 g product was isolated at a rate of 1.75, 3.42 and 0.12 g product per kg of adsorbent per hour for OR, LU and PN, respectively. Every second peak belongs to the same column housing due to alternating operation: desorption takes place 0–18 h and 18–36 h on column housing B and A, respectively.

The good agreement between the measured and predicted concentration profile demonstrates that the system is stable over time. The desorption profiles are different for each biophenol. The highest peak was observed for LU as the desorption of this material is the fastest (see Figure 7b) and it has the highest adsorbed mass. This shows the different adsorption affinities of the individual biophenols for the imprinted materials. The sensitivity analysis revealed that even with a less selective (γ , Eq. S13) column, still high purity (> 90%) can be achieved (Figure 7c). A small change ($\gamma < 2\%$) in selectivity has a negligible decrease in the purity of both OR (purity > 99.3%) and LU (purity > 99.5%). On the contrary, owing to the lower initial concentration and different adsorption isotherm properties (refer to Section 5 in

the Supporting Information), the decrease in the purity of PN down to 91.3% is more pronounced.

Membrane Separation

The nanofiltration units coupled downstream of the adsorption, enabled the waste and product streams to be concentrated, and the solvent recycled to reduce the environmental impact by minimizing the amount of solvent waste and fresh solvent usage.³³ Note that the recycled solvent is reused in the original process as it may contain process-related impurities, and therefore its use in other processes is not recommended without detailed impurity profiling. The concentrations at the retentate and permeate streams of the membrane are determined by two parameters: the rejection of the biophenols (R , Eq. 1) and the fraction of the total volumetric flow (α , Eq. 2) as shown in Figure 8. The dynamics of the concentration of the components in the permeate (C_{perm}) and retentate (C_{ret}) can be described by Equations 3 and 4.

$$\frac{dC_{ret}}{dt} = \frac{Q_f}{V_m} (C_o(t) - \alpha C_{ret} - (1 - \alpha)(1 - K)C_{ret}) \quad \text{Eq. 3}$$

$$\frac{dC_{perm}}{dt} = \frac{Q_f}{V_m} ((1 - \alpha)(1 - K)C_{ret} - (1 - \alpha)C_{perm}) \quad \text{Eq. 4}$$

where the absence of spatial gradients of concentration in the membrane cell volume (V_m) is assumed due to strong mixing induced in the recirculation loop, $C_o(t)$ is the concentration of the components at the outlet of the adsorption column, while Q_f and Q_{ret} are the feed and retentate volumetric flow rates.

Figure 8. Concentration profile map of the continuous membrane process at steady state. The color bar represents the concentration of OR at the a) retentate and b) permeate streams in g L⁻¹ as a function of the fraction of the total volumetric flow rate (α) and the rejection of the membrane (R). The contour lines represent 10% increment. Refer to Figure S2 in the Supporting Information for the concentration profile of the other biophenols.

The increase of rejection results in higher retentate and lower permeate concentrations, which favors product recovery *via* less product loss. On the contrary, the decrease of α favors product recovery, albeit the concentration in the permeate also increases. Figure 8 reveals that α has a more pronounced effect at lower rejections. Although the rejection is determined by the membrane, the α is a process parameter that can be easily adjusted to optimize the separation performance. For the best performance of the membrane separation, the rejection needs to be maximized and the α minimized. The resulting high concentrations should be monitored to avoid the precipitation of the biophenols.

The concentration in the retentate gradually builds up during the continuous process (Figure 9, Table 1). The concentration has a reciprocal relation to the selected product mass loss. By shortening the duration of the cycles, the mass loss on the column increases, while the concentration of the retentate stream increases with lower amplitude (A , Eq. S23). Apart from α , the allowed product mass loss can also be used to fine-tune the steady-state concentration in the membrane unit, and subsequently avoid precipitation of the biophenols.

Figure 9. Retentate stream concentration profile of the continuous membrane process for OR as a function of processed volume at different mass loss values. Refer to Figure S3 in the Supporting Information for the concentration profile of the other biophenols.

Table 1. The effect of choice of product mass loss on the temperature-swing cycles and the membrane unit.

Biophenol	Mass loss	^a Time per cycle	^b <i>G_{st}</i>	<i>A</i>	# of cycles to reach steady-state
[-]	[%]	[h]	[g L ⁻¹]	[%]	[-]
OR	^a 0.0	18.4	32.9	38	7
	0.1	11.0	55.3	19	11
	0.5	8.6	70.7	13	14
LU	^a 0.0	18.4	11.8	123	2
	0.1	8.4	23.9	48	5
	0.5	6.5	30.9	33	6
PN	^a 0.0	18.4	5.5	52	4
	0.1	17.5	5.8	48	4
	0.5	15.4	6.6	39	5

^aThe time per cycle equals to the required desorption and adsorption times.

Process efficiency assessment

The environmental sustainability of the simultaneous isolation process and the membrane-assisted solvent recovery were demonstrated through the estimation of the *E* factor and the ecological footprint defined in Eq. 5 and Eq. 6, respectively (Figure 10).

$$E \text{ factor} = \frac{\text{kg waste generated}}{\text{kg isolated product}} \quad \text{Eq. 5}$$

$$\text{Carbon footprint} = \frac{\text{equivalent kg of CO}_2}{\text{kg isolated product}} \quad \text{Eq. 6}$$

The continuous, stand-alone processes for the isolation without solvent recovery of one of the biophenols generates 1834 kg, 1310 kg and 6878 kg of ethyl-acetate solvent waste for each isolated kilogram of OR, LU and PN, respectively. These values correspond to 3631 kg, 2594 kg and 13617 kg of CO₂ emission, respectively. The *in line* solvent recycle enables the industrial sector to reduce the environmental burden and expenditure on fresh solvent, storage of fresh and waste solvents, transportation and disposal. The hybrid process consisting of the continuous adsorption process of a single biophenol coupled with a membrane-based solvent recovery unit resulted in a 97.5% reduction in solvent consumption. Consequently, the *E* factor of the hybrid process decreased to 67 kg kg⁻¹, 52 kg kg⁻¹ and 236 kg kg⁻¹, which corresponds to 96.4%, 96.1% and 96.6% decrease for OR, LU and PN, respectively. A more modest decrease of the carbon footprint to 3713 kg kg⁻¹, 2764 kg kg⁻¹ and 14506 kg kg⁻¹, which corresponds to 48.8%, 47.7% and 47.7% decrease was achieved, respectively. *E* factor and carbon footprint of as low as 0.00125 kg kg⁻¹ and 0.00248 kg kg⁻¹ were achieved with *in line* solvent recycle, respectively. These elements contribute less than 0.01% to the total carbon footprint of the process. PN has considerably higher environmental burden than the other biophenols due to its lower concentration in the olive leaf extract: 0.311 g PN L⁻¹ versus 0.966 g OR L⁻¹ and 1.042 g LU L⁻¹, which requires the process to run 274.8% and 424.4% longer to produce a kilogram of PN, respectively.

Figure 10. *E* factor (left columns) and carbon footprint (right columns) estimations for single biophenol isolation without (left clusters) and with (right clusters) *in line* solvent recycle, and for the simultaneous isolation process. Refer to Table S7–18 in the Supporting Information for the breakdown of calculations.

An increasingly important aspect of implementing a technology is the cost of environmental burden over economic benefits. To evaluate these factors, we propose the use of economic sustainability (ES) parameters defined for waste and emitted CO₂ as shown in Equations 7 and 8, respectively. Figure 11 shows the economic sustainability for stand-alone biophenol isolation and for the simultaneous biophenol isolation process based on the waste generated and emitted CO₂ per million dollars in 2019.

$$ES_{2019}^W = \frac{\text{kg waste generated}}{\text{value of isolated product in 2019}} \quad \text{Eq. 7}$$

$$ES_{2019}^{CO_2} = \frac{\text{kg CO}_2 \text{ emitted}}{\text{value of isolated product in 2019}} \quad \text{Eq. 8}$$

Taking into account the value of the biophenols, the difference between PN and the other three cases decreased due to the higher price for PN (Figures 11 versus 10).³⁴ Note that the price of products depends on various factors — such as scale of production, location of manufacturing — and consequently the ES should only be used for comparison purposes restricted to products with similar nature.

Figure 11. Economic sustainability for waste (left columns) and emitted CO₂ (right columns) estimations for single biophenol isolation without (left clusters) and with (right clusters) *in line* solvent recycle, and for the simultaneous isolation process. Refer to Table S7–18 in the Supporting Information for the breakdown of calculations.

Conclusions

Imprinted materials were used for the continuous and simultaneous isolation of three biophenols from olive leaf waste *via* temperature-swing adsorption. *In line* solvent recycle was realized through organic solvent nanofiltration, which enabled both the waste and biophenol streams to be concentrated, while more than 97% of the extraction solvent was saved. The biophenol-specific imprinted polymers enabled the selective scavenging of the target compounds with 95-99% purity at a rate of 1.75, 3.42 and 0.12 g product per kg of scavenger per hour for OR, LU and PN, respectively.

Mathematical models for the adsorption dynamics and the membrane separation were developed to assist with the process optimization, reducing the need for excessive experimentation. The optimized process resulted in 61% and 49% reduction of the ecological and carbon footprints, respectively. Novel metrics for the assessment of economic sustainability for waste and emitted CO₂ have been introduced.

The operation of the experimental setup was designed to be straightforward. The temperature-swing adsorption/desorption cycles are realized via diverting the flows with four-, and six-way valves, without the need for change the settings of any of the pumps and thermostats. Due to the general and expandable nature of the model, the presented methodology opens new ways for modelling of fractionation of various valuable natural compounds and allows easy optimization of production of quasi-unlimited components.

Associated content

Supporting Information

The Supporting Information is available free of charge on the ACS Publication website at DOI: 10.1021/acssuschemeng.9b04245

Chemical structures and compositions; biophenol characterization; adsorption column dynamics; adsorption isotherm expression; sensitivity analysis; effective intra-particle diffusivity estimation; calculation of the recovered and lost mass; membrane fabrication; membrane separations; green metrics calculations.

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Notes

The authors declare no competing financial interest.

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Table of Contents Graphic

Three biophenols, with pharmaceutical grade, were simultaneously isolated from agricultural waste. *In line* solvent recycle was realized through product and waste concentration using nanofiltration. *E* factor, carbon footprint and economic sustainability were assessed.