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Exploring the potentialities of a biodegradable polymeric film in sample preparation: An optimized "white" protocol to extract and quantify emerging contaminants in water

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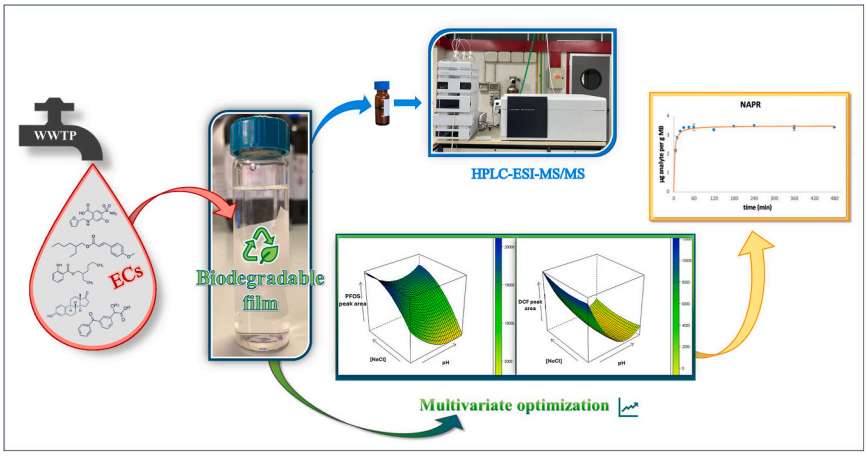
HIGHLIGHTS

- First analytical implementation of the Mater-Bi biopolymeric film in sample preparation.
- Optimization of emerging contaminants' extraction by two sequential experimental designs.
- Good performance with negligible matrix effects in real wastewater samples for 16 analytes.
- Simple, inexpensive and green fabric phase sorptive extraction-like method.
- Coupling with LC-MS/MS allowed specific and sensitive quantification in wastewaters.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: The introduction of white analytical chemistry encourages the development of methods characterized by a balance among greenness, productivity/feasibility and analytical performances. In the environmental analysis of emerging contaminants (ECs), for which high sensitivity and specificity are mandatory, the use of green and sustainable sample preparation needs to be coupled to a reliable analytical determination. Herein, an extraction method based on the use of a biodegradable polymeric film (Mater-Bi) and coupled to LC-MS/MS analysis was developed for the sensitive determination of ECs in wastewater.

Results: The interaction among a range of ECs and the Mater-Bi film (a commercially available patented blend of polybutylene-terephthalate, starch and fatty acids) was investigated by two sequential experimental designs, to simultaneously study several factors and optimize extraction efficiency. The final method, resembling a fabric phase sorptive extraction, involved pH and ionic strength modification of the sample, 1h extraction and desorption in ethanol. Satisfactory recoveries from real wastewater were obtained for sixteen analytes (56–116 %), as well as excellent precision (inter-day relative standard deviations below 10 % for most compounds).

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Matrix effect was in the range 88–116 % at the lower pre-concentration factor, but also acceptable in most cases at the higher pre-concentration factor. LODs in matrix, from 0.004 to 0.159 μg L^{-1}, were lower than or comparable to those from recent studies employing green extraction procedures. The method demonstrated its applicability to samples from wastewater treatment plants, allowing quantification of pharmaceuticals and UV filters at the μg L^{-1} and ng L^{-1} levels, respectively.

Significance: For the first time, the synthetic biopolymer Mater-Bi, so far unexplored for the use in analytical chemistry, was exploited for a green, simple and extremely cheap extraction protocol. The optimized method is suitable for several ECs, guaranteeing very good accuracy, precision and specificity, also thanks to the LC-MS/MS analysis. The evaluation by green and white analytical chemistry metrics highlighted its superiority to conventional extraction methods.

1. Introduction

In the latest years, one of the driving forces in research has been the predilection for greener approaches in several fields, including analytical chemistry. Nevertheless, scientists are becoming aware that some of the Green Analytical Chemistry principles are difficult to apply either because they undermine the reliability of the results or are not sustainable enough. Indeed, some essential analytical requirements (accuracy, precision, specificity …) are not easily fulfilled through the greenest strategies. Moreover, some practical aspects such as time and cost-effectiveness could be overlooked. Nowak et al. [1,2] recently introduced the new concept of "White analytical chemistry" (WAC), which highlights the importance of being "greener" without neglecting the value of method performance and feasibility. White analytical chemistry imposes the development of novel methods, which guarantee the achievement of accurate quantitation results with minimum use of toxic substances and waste production. These aspects are even more important when dealing with the determination of environmental contaminants. In particular, a major analytical challenge is the detection of emerging contaminants (ECs) in water, due to their "pseudo-persistence" and trace concentration levels. ECs englobe "recently appeared contaminants" but also "contaminants which have been in the environment for a while but for which concerns have been raised much more recently" [3]. When the concentration levels of these pollutants are low and interferents are present, sophisticated and energy-demanding instrumentation are generally required to reach the needed levels of accuracy, sensitivity and precision. This inherently lowers the greenness of the method that could be developed. Thus, efforts are required to limit the overall impact of the method by focusing on greener sample preparation [4].

In green sample treatment strategies, a wide range of applications based on biopolymers have been developed in the latest years. Numerous sorbents varying in form and composition have been proposed for water analysis. The most used materials in these environmental applications are cellulose, agarose, alginate, chitosan, cork and diatomaceous earth [5,6]. Among the recent forms and configurations adopted, Thin Film Microextraction (TFME) [7] and Fabric Phase Sorptive Extraction (FPSE) [8] are widespread, due to ease of use, speed and provided sensitivity. In both methods the device is immersed in the liquid samples and stirred during the extraction time. Then, desorption is performed by either a thermal process or by solvent-back extraction, for analysis by gas chromatography or liquid chromatography [9] [–] [11]. TFME devices with cork or diatomaceous earth as sorbent have been used for the extraction of emerging contaminants, such as parabens, UV filters and Bisphenol A (BPA) [12,13]. Cellulose covered with poly(tetrahydrofuran) was employed to extract BPA and two estrogens from a range of water samples [14], while a coating of polyethylene glycol was exploited for non-steroidal anti-inflammatory drugs [10]. A recent FPSE method based on cellulose covered with a Metal Organic Framework was developed for the determination of six UV filters in freshwater and seawater [15].

The natural sorbents are used either unmodified or in composite form, while other biodegradable synthetic polymers are rarely investigated [16,17]. On the other hand, a plethora of synthetic biopolymers, which have been developed during the years, are used in several fields [18] and may have great potential also in analytical chemistry and especially greener sample preparation.

In this framework, we present a systematic study exploring the analytical applicability of a biodegradable polymeric film for the extraction from water of approximately 40 ECs, including pharmaceuticals, UV filters, pesticides, hormones, tracers and perfluorinated compounds. The selected material, under the trade name Mater-Bi, is a patented blend mainly constituted of synthetic components such as polybutylene-terephthalate and/or polycaprolactone, thermoplastic starch and fatty acids [19–21]; to the best of the authors' knowledge, its analytical potentialities have never been investigated. Given its peculiar composition and therefore presence of different functional groups, it may represent an interesting choice for the interaction with analytes characterized by different properties. In the form of a film, its use as an extraction medium (for TFME or FPSE) has been tested for the considered set of analytes. A Plackett-Burmann experimental design followed by a D-optimal design were used to study the effect of a total of 7 variables on the ECs' extraction. The sample-treatment was coupled with LC-MS/MS analysis, validated and applied to different wastewater samples. Finally, its greenness and performances were evaluated by using the latest metrics proposed for green and white analytical chemistry.

2. Materials and Method

2.1. Chemicals and materials

Analytical standards were purchased from different suppliers: acesulfame K (ACS), furosemide (FRSM), hydrochlorothiazide (HCTZ), paraxanthine (PRX), theophylline (TFL), taurine (TRN), metoprolol (MTPL), clenbuterol (CLBT), terbutaline (TRBT), atenolol (ATN), carbamazepine (CBZ), benzophenone-3 (BP-3), octyl dimethyl *p*-aminobenzoate (OD-PABA), ethyl hexyl methoxy cinnamate (EHMC), ethylexyl salicylate (EHS), octocrylene (OC), perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), sucralose (SCL), nicotine (NCT), bisphenol A (BPA), estrone (E1), β-estradiol (E2), 17α-ethinyl estradiol (EE2), ibuprofen (IBU), gemfibrozil (GEM), cocaine (COCA), omethoate (OMT), daminozide (DMNZ), 2,4-dichlorophenoxyacetic acid (2,4-D), chloramphenicol (CMPH), metformin (MTF), chlormequat (CMQ) and triclosan (TCS) were from Sigma-Aldrich (St. Louis, MO, USA); caffeine (CAFF), ketoprofen (KET), naproxen (NAPR), and diclofenac (DCF) from Fluka Analytical (Saint Gallen, Switzerland), while salbutamol (SLBT) from Alfa Aesar (Haverhill, MA, USA). All analytical standards were equal or above 98 % of purity. Stock standard solutions of the 39 analytes were prepared dissolving pure standards in methanol (MeOH) or MeOH:water 1:1 (depending on their polarity) and were stored at −18 °C.

Ultra-pure water (mQ water) was obtained by using a Milli-Q-Millipore (Watford, UK) system (conductivity 0.055 μS cm^{-1}). MeOH, ethanol (EtOH) and acetonitrile (ACN) were purchased from VWR (Radnor, PA, USA). All solvents were HPLC-MS grade. Mass spectrometry grade acetic acid was purchased from VWR (Fontenay-sous-Bois, France), sodium hydroxide (≥97 %) and sodium chloride (NaCl, ≥99 %)

were provided by Sigma-Aldrich (St. Louis, USA) and hydrochloric acid by Merck (Germany). The biodegradable material used to develop the sample preparation strategy was Mater-Bi (M-B), in the form of films of 25 ± 1 μm thickness, produced by Novamont SPA. Basic chemico-physical characterization of the film was carried out and information is reported in supplementary material (paragraph S1 of SM, including Table S1 and Fig. S1).

2.2. Instrumental analysis

An LC-MS/MS system by Agilent technologies (Santa Clara, CA, USA) was used for the analyses. The HPLC (1200 series) was equipped with a binary pump, an online vacuum degasser, an automatic liquid sampler (ALS) and a thermostated column compartment. The chromatograph was coupled to a triple quadrupole mass spectrometer (model 6430) through an Electrospray Ionization source (ESI). The analyses were performed by using a method previously developed in our laboratory [22], exploiting a Kinetex® C18 Polar column (100 mm × 2.1 mm i.d.; 2.6 μm particle size) by Phenomenex (Torrance, CA, USA). Two chromatographic runs were used for the analysis of the 39 compounds, due to the different mobile phases required for the efficient ionization of the compounds. Details on the chromatographic separations are reported in supplementary material (paragraph S2 of SM).

The settings of the ESI source in both methods were: reagent gas (N_2) temperature and flow of 300 °C and 4 L min^{-1} respectively, nebulizer pressure 40 psi and capillary voltage 4000 V. The dynamic multiple reaction monitoring (d-MRM) mode was employed to maximize sensitivity. The MRM transitions and associated MS parameters are reported in Table S2. For most compounds, two MRM transitions were used, with the most intense considered as the quantifier (Q). The qualifier MRM (q) and the ratios between its area and that of the quantifier were used to confirm compound identity [23].

The Agilent MassHunter workstation software (version B.04.01) was employed for data acquisition, qualitative and quantitative analysis.

2.3. Experimental design

Two sequential experimental designs were employed to investigate the interaction of the analytes with the M-B and to optimize the sample preparation procedure. The experiments basically consisted of the following steps: spike of the analytes in 20 mL of mQ water at a certain pH and ionic strength; immersion of the M-B in a 22 mL vial and agitation (160 rpm) for a fixed amount of time; washing of the M-B with mQ water; back extraction of the analytes in MeOH. First, five factors were investigated through a screening design (Plackett-Burman) [24]: pH, NaCl concentration, temperature, film dimension and % of organic modifier (EtOH). All the variables were quantitative and were investigated at two levels (coded as −1 and + 1 and indicated in Table S3), by choosing a reasonably large domain.

A total of 8 experiments (Table 1) were performed in random order, as to estimate linear effects of the significant variables, by keeping an acceptable number of degrees of freedom [25].

After performing the 8 experiments, the responses (peak area of the analytes in the different extracts) were used to construct linear models through multivariate linear regression (MLR) and identify the significant factors.

After the screening, only three out of the five initial variables were kept for further investigation (pH, NaCl concentration, film dimension), but two more were added, including a qualitative one (time and agitation mode). Therefore, a D-optimal design was chosen to estimate linear and quadratic terms of the model, as well as some interaction terms, with an optimized set of experiments [26]. New coded and real values of the variables are shown in Table S4.

The model to be computed (with the selected interaction terms) was the following:

Table 1
experiments performed in the Plackett-Burman design.

Plackett-Burman design					
	pH	[NaCl] (mg mL^{-1})	Temperature (°C)	Film dimension (cm)	% EtOH
Exp 1	4	0	50	3x7	15
Exp 2	9	0	20	3x7	15
Exp 3	9	10	20	3x7	0
Exp 4	9	0	50	3x3	0
Exp 5	4	0	20	3x3	0
Exp 6	4	10	20	3x3	15
Exp 7	4	10	50	3x7	0
Exp 8	9	10	50	3x3	15

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 + b_{12}x_1x_2 + b_{34}x_3x_4 + b_{35}x_3x_5 + b_{45}x_4x_5$$

where Y is the response (peak areas of each analyte in the extract), b_i, b_{ii} and b_{ij} are the coefficients of the linear terms, of the quadratic terms and of the interactions, respectively. To compute this model (response surface) a minimum of 14 experiments is required, but the D-optimal algorithm suggested a higher number of experiments to optimize variance inflation factors and the informativeness of the experiments [27]. Table 2 shows the selected experiments (22) plus the 3 replicated points, chosen by applying the "D-optimal by addition" algorithm.

After performing the 25 experiments, MLR allowed to construct the models, assign them an explained variance, namely the adjusted determination coefficient (R^2_{adj}) [25], identify the significant factors and the sign of their coefficients. The results of the D-optimal design suggested the optimal conditions of the experiment, which was then tested to validate the optimization procedure.

The free software CAT [28] was used to implement the D-optimal design, for the computation of the models in both DoEs and for the graphical visualization of the response surfaces.

2.4. Sorption kinetics

The sorption kinetics were investigated by immersing the film (dimension 3 × 7 cm) in water solutions (20 mL) at a fixed concentration for different time intervals, to verify the uptake of the chemicals onto the film over time. A concentration of 10 μg L^{-1} was chosen to guarantee the solubility of all analytes and to avoid saturation of the material. The conditions of the experiments, each one in replicate, were the optimal ones (see paragraph 2.5) but the film "exposure" was for: 5 min, 10 min, 20 min, 30 min, 45 min, 1 h, 2 h, 3 h, 4 h, 6 h and 8 h. The extracts obtained after desorption of the analytes from the film were analysed, instead of the residual water, for a more accurate evaluation of the material uptake. Even if this method does not isolate the "uptake step" from the elution, the final analytes were those for which quantitative recovery from the film after sorption was already verified (see paragraph 3.1 "preliminary recovery tests"). The ratio "mass of the analyte/mass of the M-B" ($m_a/m_{M\text{-}B}$) versus time curves were constructed to study the kinetics and set the optimal extraction time.

2.5. Final procedure

Before method application, pieces of M-B of 3 × 7 cm dimensions were washed with EtOH in an ultrasonic bath for 10 min (approximately

Table 2
selected experiments of the D-optimal design; replicated experiments were the numbers 3, 8 and 15.

D-Optimal design					
	pH	[NaCl] (mg mL^{-1})	Time (h)	Film dimension (cm)	Agitation
Exp 1	6.5	0	18	3x3	horizontal[a]
Exp 2	4	15	18	3x3	horizontal
Exp 3	4	7.5	42	3x3	horizontal
Exp 4	9	15	42	3x3	horizontal
Exp 5	4	0	18	3x5	horizontal
Exp 6	9	15	30	3x5	horizontal
Exp 7	9	0	42	3x5	horizontal
Exp 8	9	7.5	18	3x7	horizontal
Exp 9	4	15	30	3x7	horizontal
Exp 10	4	0	42	3x7	horizontal
Exp 11	6.5	15	42	3x7	horizontal
Exp 12	9	7.5	18	3x3	rotatory[b]
Exp 13	4	15	18	3x3	rotatory
Exp 14	4	0	30	3x3	rotatory
Exp 15	6.5	0	42	3x3	rotatory
Exp 16	6.5	7.5	30	3x5	rotatory
Exp 17	4	15	42	3x5	rotatory
Exp 18	4	0	18	3x7	rotatory
Exp 19	6.5	15	18	3x7	rotatory
Exp 20	9	0	30	3x7	rotatory
Exp 21	6.5	7.5	42	3x7	rotatory
Exp 22	9	15	42	3x7	rotatory

[a] horizontal agitation: 160 rpm.
[b] rotary agitation: 40 rpm.

a total of 200 mL for 10 films), to remove possible interferents and avoid any contamination, and let dry under a fume hood. Concentrated hydrochloric acid (37 % v/v) was added dropwise to the water samples, till they reached pH 2, while NaCl was added up to a concentration of 30 mg mL^{-1} (3 % w/v). Then, the M-B was immersed in 20 mL of the sample, placed in a 22 mL glass vial (bottom diameter 2.3 cm, height 8.5 cm). An extraction of 1 h under gentle rotatory agitation (40 rpm) was performed, followed by a washing of the films with 5 mL of acidified water (pH 2), repeated twice. Then, the films were dried on clean laboratory paper and a back extraction with 10 mL of EtOH was performed, by placing the vials in an ultrasonic bath for 10 min. An aliquot of 1 mL was subjected to dilution with water (extract/water in the proportion 2:1, with an overall preconcentration factor of 1.33), filtered through a 0.22 μm PTFE syringe filter and subjected to the LC-MS/MS analysis. In alternative, if lower concentrations were expected, 1 mL of extract was filtered, evaporated under N_2 flow and reconstituted with 100 μL of MeOH:H_2O, prior to LC-MS/MS analysis (overall preconcentration factor of 20).

2.6. Method performances

The overall method was evaluated in terms of trueness (recovery and matrix effect), precision, limit of detection (LOD), limit of quantitation (LOQ), linearity range and specificity, considering real samples.

The method validation was performed by using a pool of waters coming from a wastewater treatment plant (WWTP). Thirteen different samples were collected at the outlet of the secondary treatment and 50 mL of each sample was taken to create the pool. This was used for the evaluation of recovery (R), matrix effect (ME) and all the other figures of merit in real samples.

In particular, the pool was divided into different aliquots to prepare the non-spiked sample (NS), the sample spiked before extraction (SB) and the sample spiked after extraction (SA).

The recovery tests were performed at two concentrations levels named as low (2 μg L^{-1} added to the initial sample) and high (10 μg L^{-1} added to the initial sample).

Recovery (R%) was calculated using the following expression:

$$R\ (\%) = 100 * \frac{A_{SB} - A_{NS}}{A_{SA} - A_{NS}}$$

where, for each analyte, A_{SB} and A_{SA} represent the chromatographic peak area in the sample spiked before extraction and in the sample spiked after extraction, respectively. The concentration of the analyte in the sample spiked after extraction corresponds to a theoretical 100 % recovery. The term A_{NS} represents the area of the analyte in the non-spiked sample.

ME% was evaluated by the following expression [29]:

$$ME\ (\%) = 100 * \frac{A_{SA} - A_{NS}}{A_{STD}}$$

where $A_{SA,}$ A_{NS} and A_{STD} represent the chromatographic peak area of each analyte in the sample spiked after extraction, in the non-spiked sample and in a neat standard solution, respectively. By using this definition of ME, a value below 100 % indicates signal suppression, while a value above 100 % indicates signal enhancement.

Procedural precision was evaluated by performing the recovery tests in triplicates during the same day, to determine intra-day relative standard deviation (RSD%) and during 3 different days to determine the inter-day relative standard deviation.

External calibration curves (calibration standards prepared in neat solvent) were used for quantitation, constructed by using solutions at a concentration of LOQ, 0.5 μg L^{-1}, 2 μg L^{-1}, 5 μg L^{-1}, 10 μg L^{-1}, 25 μg L^{-1}, 50 μg L^{-1}. Linearity was checked by looking at the determination coefficient as well as the random distribution of the residuals of the linear model. The LOD and LOQ were estimated as a signal to noise ratio of 3 and 10, respectively, considering the noise observed in real samples. The LOQ was taken as the first point of the calibration curve.

Finally, specificity was guaranteed by acquiring two MRM transitions (quantifier and qualifier) for each analyte and by checking the ratio between their peak areas, as well as the retention times.

2.7. Real samples

Different samples were collected from a WWTP in Northern Italy, at the outlet of the secondary treatment. They were immediately filtered through filter paper and a 0.05 % of MeOH was added to inhibit bacterial activity [30,31]. Then, they were stored at 4 °C in the dark, until processing (within 2 days). After agitating the samples (approximately 1 L), 20 mL of each of them were withdrawn and subjected to the optimized sample pre-treatment and subsequent LC-MS/MS analysis. Different dilutions were applied depending on the sample, to guarantee the analytes' concentrations fall within the linearity range.

3. Results and discussion

3.1. Preliminary recovery test

Due to the diverse nature of the studied analytes (hydrophobic, acidic, basic) and the lack of previous investigations, some preliminary evaluations were necessary, to plan the optimization strategy. According to the information available by the producer, as well as present in the literature [19,32–34], M-B is mainly constituted of synthetic

components such as polybutylene-terephthalate and/or polycaprolactone, thermoplastic starch and fatty acids. Thus, the presence of multiple functional groups may lead to diverse interaction mechanisms. A first investigation on the affinity of the analytes for the film material was performed by simply spiking a small volume of a standard solution (containing all analytes in MeOH) onto small pieces of the M-B and letting them dry. The films were rinsed with water to remove all substances with no or weak interaction with the polymer surface and then an elution with 10 mL of MeOH was performed in an ultrasonic bath. Both the rinse and elution solutions were analysed by HPLC-MS/MS to determine the washed, eluted and retained fractions of each compound. The results indicated a rather heterogeneous behaviour, depending on the physico-chemical properties of the compounds and in particular, their distribution coefficient (logD), which is related to hydrophilicity/hydrophobicity. While the partition coefficient (log K_{ow}) is informative for molecules in the neutral form, logD takes into account all neutral and charged forms of ionizable molecules and depends on the pH of the solution [35]. A clear distinction was observed among three groups, depending on the recovery in the extract: R%<40 (G1); 40<R %<60 (G2); R%>60 (G3). The graphs with single recovery values are shown in Supplementary material (Fig. S2). G1 included mainly rather polar analytes ($logD_{pH7}<0$) which were almost completely removed by the washing step. PFOA and PFOS also fell into G1; they are characterized by a $logD_{pH7}$ of approximately 1.6 and 3 respectively, but also present a charged group at neutral pH, due to the $pk_a < 1$ (chemical properties of the analytes in Table S5). G2 mainly included mid-polar analytes with acidic or basic properties ($-1<logD_{pH7}<3$), while G3 was constituted by rather hydrophobic analytes ($logD_{pH7}>3.5$), such as UV filters, which showed a high affinity for the polymer and were almost quantitatively recovered in the eluate; the only exception was CLBT, which has a $logD_{pH7}<0$, but unexpectedly showed affinity for the material. Along with the recovery, the matrix effect in the extracts was estimated and resulted moderate or negligible for most compounds, indicating that no interference was caused by chemicals released by the polymer during the MeOH desorption. The mass balance calculated by comparing the analysis of the washing solution and eluate indicated that no residual analyte mass was retained by the material, except for EHS, for which 4 % of the mass was detected in the wash, but only 46 % in the eluate. Nevertheless, due to low sensitivity for this analyte, this may be related to the uncertainties in the analytical results.

Given the mass balance obtained from these preliminary experiments, the desorption conditions used for the following optimization experiments were always the same. Nevertheless, when the best extraction conditions were determined, further tests were performed to choose a greener desorption solvent and to define the number of back extractions.

3.2. Uptake investigation by screening experimental design

The first evidence revealed by the preliminary tests was that the main interactions among the M-B and the analytes were hydrophobic. Indeed, both the water-material contact angle and the functional groups identified by the FT-IR measurement also suggested hydrophobic properties of the film (see SM, paragraph S1 and Table S1). The aim of the study was to use the M-B in an extraction configuration in-between TFME and FPSE. The sorbent volume was rather small in all tests, given the surface area (from 9 to 21 cm^2) and especially the thickness of the film (approximately 20 μm). A relatively small volume of sample (20 mL), similar to those used in FPSE applications [9], was set. The different properties of the large set of analytes investigated suggested that a different behaviour could be observed, possibly leading to both exhaustive (SPE-like) or non-exhaustive (SPME-like) methods. Nevertheless, due to the analysis in LC-MS/MS, a desorption step in solvent was unavoidable, thus a potential non-exhaustive method would definitely lead to higher LODs (if compared to thermal desorption).

To optimize the procedure and understand the analytes' sorption mechanisms several variables needed to be investigated. Given both the high number of analytes and potential variables, a multivariate approach was chosen, in order to provide a rational and systematic optimization. The choice of the variables was performed by considering literature works regarding the extraction from water of the considered compounds based on solid sorbents. In most cases, sorbent amount, pH, ionic strength, extraction time, desorption time and solvent are considered [12,13,36–39]. Five potentially influent variables were initially selected and investigated through a Plackett-Burman (P-B) design, which allows to rapidly screen several factors with few experiments. These variables were pH (range 4–9), NaCl concentration ([NaCl], range 0–10 mg mL^{-1}), temperature (T, range 20–50 °C), film dimension (F_{dim} range 3 × 3 cm - 3 × 7 cm) and % of an organic modifier (EtOH, range 0–15 % v/v). The levels were chosen so as to be wide enough to observe an effect but not too large to avoid that the effect of one variable would "cover" those of the others. The agitation mode and time were kept constant, as well as the desorption conditions (for the reasons discussed in paragraph 3.2). The agitation mode selected for the screening design was a horizontal shaker, operating with a water bath and equipped with a thermostat. The use of other instrumentation available in the laboratory, such as a rotary agitator or an ultrasonic bath, would not have allowed to control the temperature. Regarding time, it was kept constant for simplicity and a long extraction (24h) was chosen to try to favour the sorption, even in the case of possible low affinity for the material.

Eight experiments were performed to define the coefficients of 5 variables plus the constant term, thus leaving 2 degrees of freedom for experimental variance estimation. The outcome of the P-B design allowed to define the most significant variables affecting the sorption onto the M-B. The chosen response was the extraction efficiency, represented by the analytes' peak area in the eluate. The MLR models were computed for the single compounds, to better understand the interaction among them and the extraction medium.

3.2.1. Non-significant models

The outcomes of this first experimental design highlighted different behaviours of the analytes. For ACS, TRN, OMT and PRX + TFL the models could not be computed, since no peaks were observed in the extracts, indicating completely ineffective extraction. For some polar analytes (CAFF, HCTZ, MTF, ATN, SLBT, TRBT, MTPL, CLBT, COCA, 2,4-D, CMQ, NCT) none of the variables resulted statistically significant, due to extremely low peak areas in the extracts and high variability. For EHS, BPA and E2 higher peak areas were observed, but the variance was still too high to identify any effect of the variables. On the other hand, for BP-3, OD-PABA, EHMC, OC and TCS, a low RSD% was observed among the experiments, thus models were not statistically significant, but in this case the responses were always rather high, indicating effective extraction by the material. Since these analytes possess high logD, independently from the pH, hydrophobic interactions [40] between them and the M-B polyester bulk is highly probable. Moreover, the presence of a fatty acid component in the material [20] could enhance the lipophilic properties.

3.2.2. Significant models

For the remaining 13 analytes, linear models were satisfactory, highlighting the different effects of the variables. The results are shown in Table 3, including explained variance (R^2_{adj}), significant coefficients and their sign in affecting the responses. The variables demonstrated to affect the analyte interaction with the M-B film in the following manner.

- The variable pH was significant for all NSAIDs, GEM, PFOS and FRSM and always with a negative sign, suggesting better interaction with the medium at lower pH. The chemicals for which this effect was observed possess a pKa from 3.65 (FRSM) to 4.85 (IBU) (Table S5), except for PFOS, for which it is even lower. This indicated that the protonated form of these analytes (present in higher % in

Table 3
details on the linear models obtained by the P–B design: explained variance (R^2adj), statistical significance of the coefficients and their sign in the model.

Analyte	Explained variance	Variables Significance				
		pH	[NaCl]	T	F_{dim}	EtOH
SCL	0.99	NS	*[a]	**	NS[b]	*(+)
PFOA	0.78	NS	* (+)	NS	NS	NS
PFOS	0.97	*(−)	**(+)	NS	NS	*(−)
KET	0.99	**(−)	NS	**(−)	**(−)	NS
NAP	0.99	**(−)	NS	**(−)	**(−)	NS
IBU	0.996	**(−)	NS	**(−)	**(−)	NS
DCF	0.99	**(−)	NS	**(−)	*(−)	NS
GEM	0.93	*(−)	NS	NS	NS	NS
FRSM	0.88	*(−)	NS	NS	NS	NS
CMPH	0.81	NS	NS	NS	*(+)	NS
CBZ	0.83	NS	NS	NS	*(+)	NS
E1	0.91	NS	NS	NS	*(+)	*(−)
EE2	0.87	NS	NS	NS	NS	*(−)

[a] the asterisks indicate the confidence level in the statistical significance of the coefficients: * p value <0.05; ** p value <0.01; *** p value <0.001.
[b] NS= not significant.

those experiments where pH was 4) has a higher interaction with the M-B, probably through hydrogen bonds or Van der Waals forces. Indeed, the material is constituted of a polyester (polybutyleneterephthalate PBTA) bulk [19] and the FT-IR measurement showed the presence of C═O groups, which could act as H-bond acceptors, but also OH groups (probably part of the starch and/or fatty acid component), which could take part in dipole-dipole interactions.

- Regarding NaCl concentration, it positively affected the extraction efficiency of the more polar analytes, namely PFOA, PFOS and SCL, through a salting out effect [41,42].
- Temperature was significant for NSAIDs, with a negative sign, indicating a favoured extraction at lower temperatures, while the contrary was observed for SCL.
- The film dimension was the only significant variable for the extraction of CMPH and CBZ, with a slight positive effect indicating that weak interactions could be favoured by a higher surface area. Surprisingly, this variable showed an opposite effect on NSAIDs. This counterintuitive result may be due to matrix effects, since more NaCl could have remained on the surface of larger film pieces, apparently decreasing the extraction efficiency. This apparent lower extraction efficiency was indeed probably related to ion suppression given by residues of NaCl. This phenomenon, namely the ability of non-volatile salts to interfere with the ionization processes, is largely documented in the literature [43,44]. It could be related to charge competition, decreased volatility of the eluate due to the salt presence and coprecipitation of the analytes with the salt [43,45]. For this reason, in the subsequent experiments, matrix effect was always evaluated, and results normalized before model computation.
- Finally, EtOH addition was found to be slightly significant only in 4 cases (SCL, PFOS, E1 and EE2), with a negative effect for 3 out of the 4 analytes.

Given these results, in the following experiments, EtOH addition was no longer considered, and T was set at the lowest value, with the additional benefit of lowering energy consumption. The other variables were further investigated through quadratic models, to optimize the procedure for the highest possible number of analytes.

3.3. Optimization of the procedure by D-optimal design

The experimental design chosen for the following optimization was the D-optimal, thanks to its versatility, customizable models and low experimental effort. The main problem encountered was the practically null extraction of the more polar analytes. Therefore, two variables were added at this stage, namely time and agitation mode, to try to enhance interaction with polar analytes. In the P-B design the experiments lasted 24h, so a large domain was selected for this variable (18–42h), while rotary agitation (40 rpm) was added as an option, to verify if it could differently affect the thickness of the water boundary layer formed at the surface of the film [46].

3.3.1. Non-significant models

Unfortunately, the results of the D-optimal basically resembled those of the screening design, with recovery of more hydrophilic compounds (ACS, TRN, OMT, PRX + TFL, CAFF, HCTZ, MTF, ATN, SLBT, TRBT, MTPL, CLBT, COCA, 2,4-D, CMQ, NCT) once again not acceptable (below 5 %) in all experiments; consequently, their models were not significant. The P-B model for SCL, CMPH and CBZ had highlighted the influence of some of the variables, which were set in these new experiments at the best value suggested (higher film dimension). Still, in this case, negligible recovery in all the experiments was observed for these analytes and models were not significant. On the other hand, the efficient extraction of more hydrophobic analytes was confirmed. E1 and EE2 recoveries were improved thanks to the removal of EtOH and their recovery was confirmed to not be affected by the other variables.

3.3.2. Significant models and variables' effect

In other cases, the performance of more experiments, the inclusion of additional variables and the better estimation of experimental variance allowed to identify additional effects. Table 4 summarizes the outcomes of the D-optimal design for the analytes which were characterized by satisfactory models (R^2_{adj}≥50 %).

It is noteworthy that all NSAIDs and GEM showed the same type of models: pH was the most important variable, with a negative effect and a quadratic trend. For BP-3, agitation showed a slight positive effect (rotary agitation preferable) as well as an interaction with the film dimension. This was the only analyte for which also time seemed to weakly influence recovery. CLBT was the only compound for which the

Table 4
details on the quadratic models obtained by the D-optimal design: explained variance (R^2adj), statistical significance of the coefficients and their sign in the model.

Analyte	Explained variance	pH (4–9)	[NaCl] (0–15 mg mL^{-1})	Film dimension (3×3 - 5×7 cm)	pH^2	Others
PFOA	0.49	NS	*[a](+)	*(+)	NS[b]	**pH x [NaCl]** *(−)
PFOS	0.76	**(−)	***(+)	**(+)	*(+)	**[NaCl] ^2** *(−)
KET	0.85	***(−)	NS	NS	***(+)	/
NAP	0.91	***(−)	NS	NS	***(+)	/
IBU	0.90	***(−)	NS	NS	***(+)	/
DCF	0.82	***(−)	NS	NS	***(+)	/
GEM	0.88	***(−)	NS	NS	**(+)	/
CLBT	0.77	**(+)	NS	***(+)	**(−)	/
FRSM	0.90	***(−)	NS	NS	NS	**[NaCl] ^2** ***(+)
BP-3	0.51	NS	NS	NS	NS	**Time** * (+) **Agitation** *(+) **Film x agitation** **(−)

[a] the asterisks indicate the confidence level in the statistical significance of the coefficients: * p value <0.05; ** p value <0.01; *** p value <0.001.
[b] NS= not significant.

pH variables had a positive coefficient, indicating better extraction at basic pH; this was not surprising, due to its strongest basic pk_a of approximately 9.6 (Table S5). For EHMC and OC, one of the variables resulted slightly significant: rotary agitation seemed to favour the extraction, even though the models' explained variance was low (34 and 38 %).

Since quadratic and interaction terms were statistically significant in some of the models, the response surfaces were visualized, to identify the optimal experimental setting. The response surfaces and the graphs indicating coefficients' magnitude and confidence intervals of all significant models are reported in supplementary material (Fig. S3). The response surfaces of PFOS (the analyte with the most complex model) and DCF, as NSAIDs representative, are shown in Fig. 1 and Fig. 2, respectively.

The PFOS response surfaces highlighted that the salt concentration and film dimension had an overall similar effect on the extraction (even if of slightly different magnitude), while the effect of pH was less influent on the response, since characterized by a positive linear term, but an opposite (negative) quadratic term. On the other hand, the NSAID's response surfaces clearly indicate the strong effect of pH, while a slight, non-statistically significant effect was given by salt concentration. By evaluating these models, the best conditions were identified at the extreme of the domain, at pH coded level −1 and [NaCl] coded level +1. The CLBT model was completely different (Fig. S3), going in an opposite direction compared to all other compounds. Indeed, the graph clearly shows a maximum corresponding to the +1 level of film dimension (in line with the other analytes), but also to the 0 level of pH, indicating best results at neutral pH. Unfortunately, even in these conditions, the CLBT recovery was only approximately 30 % and since its optimal pH conditions were not compatible with those of the majority of the other analytes, it was not further considered.

However, the recoveries obtained in the optimal conditions within the domain were not satisfactory for some analytes. In fact, while DCF, BP-3, OD-PABA, EHMC, OC, E1, E2, EE2, BPA and TCS showed a maximum recovery of at least 70 % in the best experiment, approximately 50 % recovery was observed for GEM and lower values (around 10 %) were observed for the other analytes. Therefore, the final tests were performed outside the experimental domain investigated so far.

Despite the high number of variables considered, both experimental designs indicated a rather poor affinity of the polar analytes for the M-B. Thus, the final optimization only concerned 18 out of the initial 39 analytes, noteworthily, all characterized by a logKow>3, except for the amphiphilic PFOA and PFOS.

3.4. Final procedure and sorption kinetics

Since the experiments performed so far suggested a higher interaction between M-B and the acidic analytes in their protonated form, a further test was performed by setting the pH at 2. Indeed, based on their pk_a (ranging from 3.5 to 4.85), approximately 100 % of their protonated form should be present at pH = pk_a-2. Before this test, a solution containing all the analytes at pH 2 was kept in the dark for 24 h, confirming their stability for this duration (data not shown). Moreover, M-B was immersed in acidified water for the same time, then, the analytes were added to this acidified solution and matrix effect was checked. No signal suppression nor enhancement were observed, indicating that M-B was stable at the tested pH and no release from the material affected the analytes' ionization.

The final optimization test involved 3 different procedures, tested in triplicate, which are synthesized in Fig. 3. In test 1, the best extraction conditions according to the experimental design were applied: i) a film dimension of 3 × 7 cm, since for all compounds a higher surface area led to a higher extraction efficiency; ii) a time of 24h, since this variable had a slight positive effect only for one analyte (BP-3); iii) agitation through a rotary system, which favoured the extraction of some UV filters. Regarding the most important variables, namely pH and [NaCl], they were set outside the domain, at a value of 2 and 30 mg mL^{-1} respectively, to verify their trends and improve the recovery of several analytes. In the tests 2 and 3, the extraction conditions were the same, but the subsequent steps were changed (Fig. 3). In particular, the film wash was performed with either pure (test 2) or acidified mQ water (test 3), while desorption was alternatively performed with 10 mL of MeOH (test 2) or EtOH (test 3), to improve the greenness of the method.

The outcome of these tests is shown in Fig. 4. All the tests gave good results, confirming that choosing more extreme values of both pH and salt concentration were definitely beneficial for the extraction efficiency. In addition, maintaining an acidic pH also in the washing solution revealed to be a good choice, to avoid the return of a small % of acidic drugs to the deprotonated form, thus decreasing the interaction strength with the M-B. Tests 2 and 3 gave excellent results, both in terms

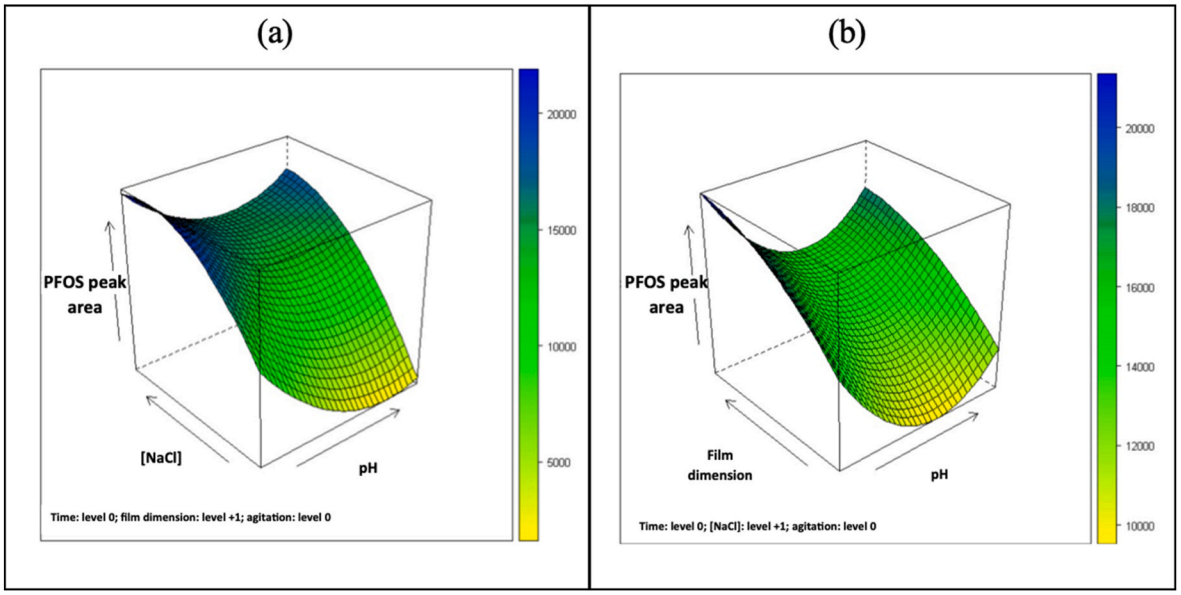

Fig. 1. Response surfaces of PFOS model, highlighting the effect of salt concentration ([NaCl]), film dimension and pH on extraction efficiency. (a) Response vs [NaCl] and pH; (b) response vs Film dimension and pH.

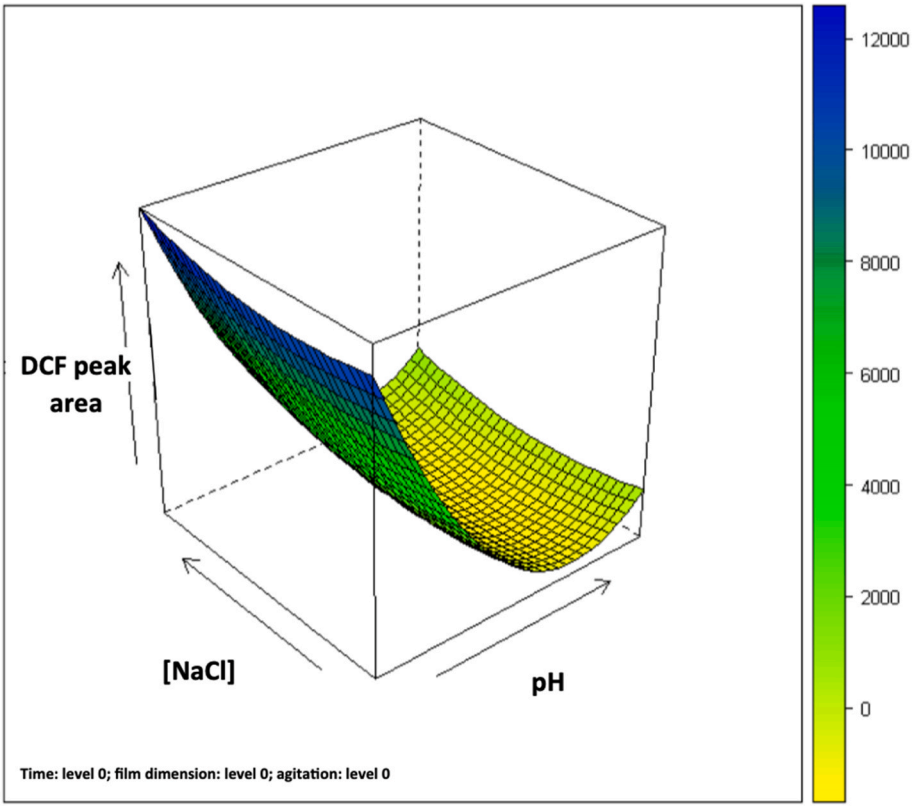

Fig. 2. Response surface of DCF model (NSAIDs representative), highlighting the effect of pH and [NaCl] on extraction efficiency (Response vs pH and [NaCl]).

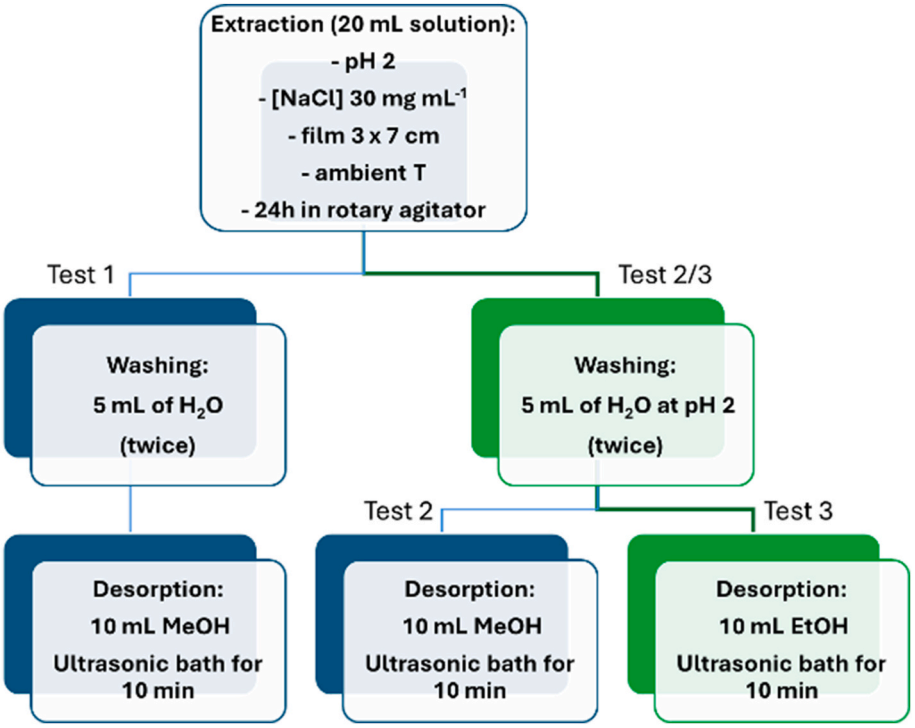

Fig. 3. Scheme of the final optimization tests (external to the experimental design).

of recovery and precision, thus EtOH was chosen as desorption solvent in the final procedure, due to the greener properties of this alcohol.

With the defined conditions for the extraction and desorption, the developed method resembled a FPSE. Since this is an equilibrium-based technique, extraction time should be tuned to guarantee that equilibrium is reached [36], but analysis throughput should be considered as well. To identify the minimum time required to have a quantitative recovery at equilibrium, some experiments on the sorption kinetics were

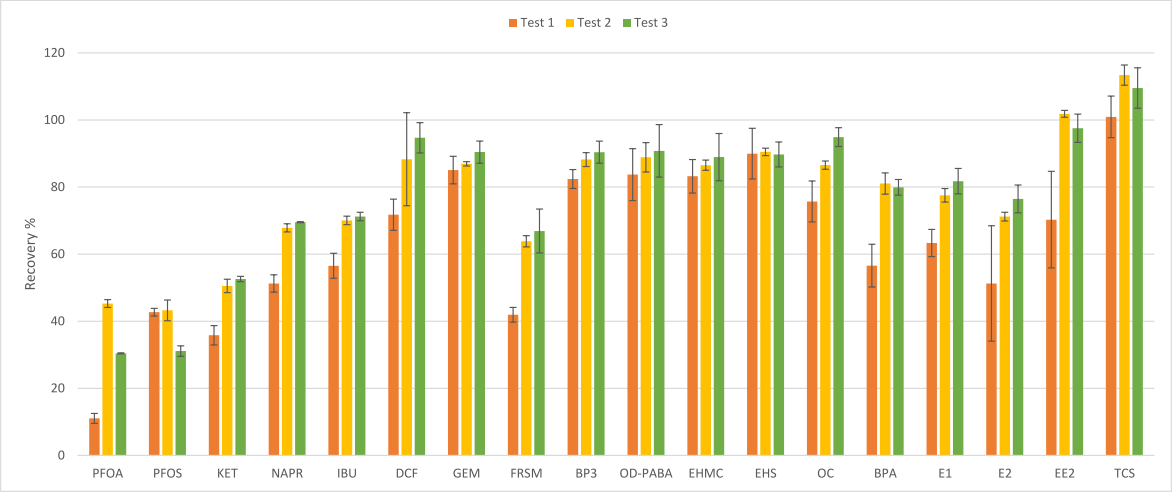

Fig. 4. Results of the final optimization tests, in terms of recovery of the analytes from spiked mQ water.

performed (paragraph 2.4 of "Materials and Method").

The kinetics resembled the trends reported in similar works [10,47] and, based on the equilibrium time, two cases were observed. Fig. 5 shows the curve obtained for NAP and PFOA, as representative of the two cases (all curves are reported in SM, Fig. S4). In the first case, a rapid increase in the concentration of the analyte in the final extract was observed, with equilibrium probably already reached after 30 min. For the two perfluorinated compounds, at least 4 h should have been

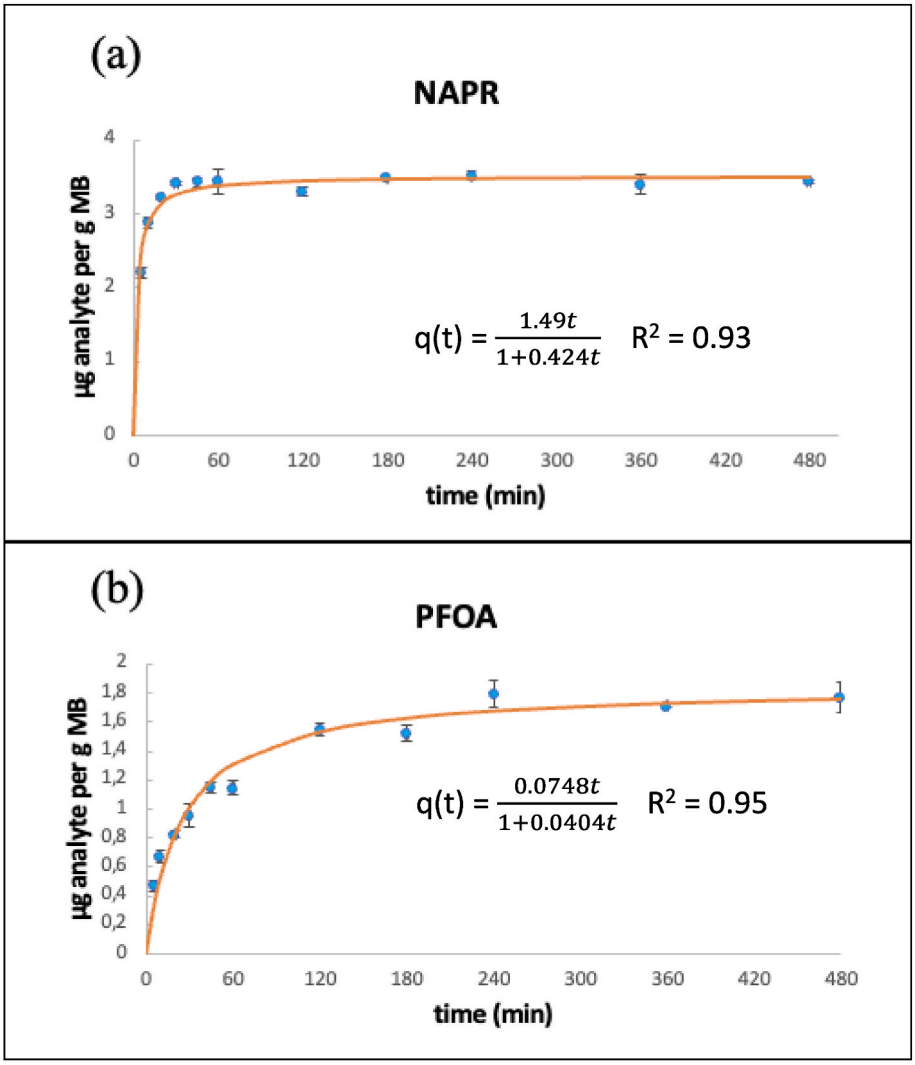

Fig. 5. Uptake curves of NAP and PFOA, as representatives of the two different behaviours in the sorption kinetics.

necessary, but the curve trend seemed to suggest that equilibrium was not completely reached after 8h. The PFOA and PFOS long equilibrium time, and consequent low recovery, are probably due to their presence in anionic form even at low pH. A further increase in ionic strength may favour and speed up their quantitative extraction, but excessive salt concentration would probably cause signal suppression.

For this reason, the proposed procedure, with an extraction time of 1h, is considered suitable for the determination of the 16 analytes with good recovery and rapid equilibrium, namely the six pharmaceuticals (NSAIDs, GEM and FRSM), the five UV filters, the three estrogens, the additive BPA and the anti-septic TCS.

3.5. Analytical figures of merit and comparison with similar methods

In order to validate the method on real samples, the optimized procedure (paragraph 2.5 of mat&met) was tested on a pool of water samples coming from a WWTP and all the method figures of merit were determined, by considering the whole sample treatment coupled to LC-MS/MS analysis. Table 5 summarizes the obtained validation parameters.

The careful accuracy study on the pooled real waters demonstrated small differences between model samples (mQ water spiked with the analytes) and real samples (Fig. S5). Indeed, satisfactory recoveries (range 70–120 %) [23] were obtained for most analytes at both investigated spike levels (low and high), and 9 out of 16 reported values above 80 %. Recovery was calculated for both preconcentration factors (PF) that were used for ME% evaluations, showing no significant differences (and therefore no loss during the evaporation steps). ME%, calculated at the two different PF, was excellent at 1.33 PF (range 88–116 %), while acceptable at PF = 20 for all compounds, except OC. Nevertheless, ME% was checked for each single sample and results were corrected if ME% was outside the acceptable range. The intra-day and inter-day precision assays indicated an excellent repeatability of the procedure. In fact, at both spike levels, intra-day repeatability was between 3 and 11 %, except for FRSM. Also inter-days RSD% were rather good, being below 9 % for 12 analytes, and slightly below 20 % only for FRSM. This analyte also showed lower recovery, maybe due to a less specific interaction with M-B compared to the other chemicals. The calibration curves in neat solvent showed good linearity ranges (from LOQ to 50 μg L^{-1}), with R^2 values going from 0.9904 to 0.9981 for the 16 analytes. LODs and LOQs were in the order of ng L^{-1} for 9 out of 16 analytes, and still well below 1 μg L^{-1} for the others. LOQs were compared with those obtained by similar works, but generally few analytes were in common. Table S6 collects ten papers concerning green strategies for ECs determination in water [10,14,15,36,37,48–52]. The papers were selected if at least two analytes were in common with our study and if similar pre-treatment strategies were used. The present study mostly provided better sensitivity, with few exceptions. The work from Racamonde et al. [10] of a method based on FPSE followed by derivatization and GC-MS, showed lower LOQs for NSAIDs compared to our work. Still, the authors evaluated LOQs by spiking ultrapure water, thus not taking into account the possibly higher noise in real samples. Also, the work from Kumar et al. [14] gave better LOQs for BPA, E2 and EE2, but once again, LOQs were evaluated by considering spiked distilled water, and the lowest point of the calibration curves was 1 μg L^{-1}, a value above the LOQs reached by the present method. For a more general comparison with the considered papers, the number of target analytes, specificity, precision and commercial availability of the used

Table 5
Figures of merit of the overall method.

Analyte	Linearity		Overall method sensitivity (μg L^{-1})	Overall method sensitivity (μg L^{-1})	Recovery (%) (n = 7)		Precision (RSD %)		ME (%)	
	R^2	Range (μg L^{-1})	LOD	LOQ	LCL[a]	HCL[b]	**Intra-day (n=3)**	**Inter-day (n=7, 3 days)**	***PF = 1.33* (n=7)**	***PF = 20* (n=7)**
KET	0.9958	0.024–50	0.024	0.081	80 ± 3	58 ± 4	10	7	101 ± 6	93 ± 8
NAPR	0.9951	0.004–50	0.004	0.014	80 ± 3	73 ± 4	8	6	101 ± 6	83 ± 9
IBU	0.9940	0.012–50	0.012	0.040	78 ± 6	71 ± 5	9	7	94 ± 9	57 ± 13
DCF	0.9943	0.006–50	0.006	0.019	116 ± 7	93 ± 12	11	13	104 ± 14	53 ± 21
GEM	0.9940	0.006–50	0.006	0.020	95 ± 3	90 ± 4	6	4	102 ± 5	58 ± 9
FRSM	0.9904	0.072–50	0.072	0.240	58 ± 5	56 ± 10	29	19	105 ± 24	74 ± 8
BP-3	0.9937	0.009–50	0.009	0.029	97 ± 2	91 ± 6	7	6	104 ± 4	66 ± 12
OD-PABA	0.9915	0.013–50	0.013	0.044	93 ± 3	90 ± 7	6	8	99 ± 7	75 ± 8
EHMC	0.9763	0.019–50	0.019	0.063	76 ± 4	77 ± 6	8	7	99 ± 8	60 ± 5
EHS	0.9978	0.159–50	0.159	0.526	84 ± 12	83 ± 7	11	8	106 ± 16	62 ± 13
OC	0.9927	0.103–50	0.103	0.339	72 ± 4	67 ± 6	6	9	88 ± 13	39 ± 9
BPA	0.9981	0.053–50	0.053	0.178	75 ± 11	79 ± 4	6	6	92 ± 15	76 ± 16
E1	0.9957	0.073–50	0.073	0.243	87 ± 4	81 ± 5	3	6	102 ± 10	77 ± 9
E2	0.9904	0.066–50	0.066	0.220	79 ± 1	74 ± 9	7	12	98 ± 11	70 ± 11
EE2	0.9961	0.026–50	0.026	0.086	90 ± 17	96 ± 12	8	12	99 ± 6	70 ± 10
TCS	0.9980	0.005–50	0.005	0.016	102 ± 4	99 ± 5	8	5	116 ± 8	65 ± 19

[a] LCL = Low Concentration Level.
[b] HCL= High Concentration Level.

media were taken into account. Most studies focused on a small set of emerging contaminants (≤10) and a detector less specific than tandem MS is employed in half of the considered works. Achieved precisions (intraday RSD%) are always comparable to those obtained. Still, the most important aspect to consider is that all works, with the only exception of Allgaier-Díaz et al. [37], use in-lab prepared devices, thus requiring a lot of experimental effort, costs and difficult lab-to-lab transferability. Instead, the proposed method involves the use of a commercially available and extremely cheap biopolymer.

3.6. Greenness evaluation

The eco-friendly characteristics of the proposed method were evaluated by one of the currently most employed metrics, namely the AGREE software [53]. This tool allows to give different weights to the different sub-scores (one for each principle of the green analytical chemistry), depending on the specific application. The overall score gained by the developed method was 0.6 (Fig. 6a, details in Fig. S6).

It must be noted that the worst scores were received in the principles related to instrumental analysis (principles 3 and 9). Then, bad scores were assigned also to the sample treatment positioning, sample amount, automation and toxicity. It must be noted that the analysis of environmental contaminants requires high specificity and low detection limits, thus making the use of "off-line" analyses by high-energy consumption instruments mandatory [1]. For this reason, a minimum weight was given to the sub-score related to these aspects, to limit the impact on the overall score. Also sample amount (20 mL) may be considered not minimal (principle 2 score was low); however, in the determination of emerging contaminants, water samples of 500 mL or even 1 L are quite common, especially in the still widespread SPE technique.

Finally, even if no harmful solvents or materials are involved in the sample treatment, toxicity score was low, due to the consumption of approximately 5 mL of ACN for each LC-MS/MS analysis. Once again, a low weight was given by the authors to this principle, since related to the unavoidable use of advanced instrumental analysis. Indeed, by only considering sample treatment, no toxic solvents were used (the final solvent chosen for pre-washing of the M-B and desorption was EtOH). On the other hand, lack of automation is actually a flaw of the developed method (low score for principle 5), but an automated system based on the used material may be implemented in the future.

In addition, the method was evaluated in terms of costs. Even though the cost is not included in the green principles, it is strongly related to sustainability and considered by other metrics, such as the RGB algorithm [1]. The M-B film is extremely cheap (approximately 0.3 € per m^2), and a cost of 0.001 € per sample was estimated. Considering the example of a classical sample treatment, such as SPE, an average cost of 10 € per cartridge is common; it follows that the proposed strategy provides a huge advantage in terms of costs, without sacrificing performances.

The method was also evaluated through the RGB algorithm in order to provide an overall score considering the principles of white analytical chemistry. Since the punctuation of this system is more arbitrary than the previous metric, comparisons make more sense than absolute evaluations. Therefore, the present method was compared to another used in our laboratory for the determination of the same analytes in waters by SPE-LC-MS/MS [54]. No further methods were used, due to the low overlap of the considered analytes with the current study. Indeed, other green strategies often focus on a small set of analytes, with few in common with the developed method. The result of the RGB scores is shown in Fig. 6b, indicating a superiority of the present strategy (score 83.4) compared to the classical SPE (score 61.4). Indeed, the M-B method gained a higher sub-score in all the set of principles (red, green and blue), thanks to the rather satisfactory analytical performances, the eco-friendly characteristics and sustainability of the sample pre-treatment as well as the good throughput of the overall method.

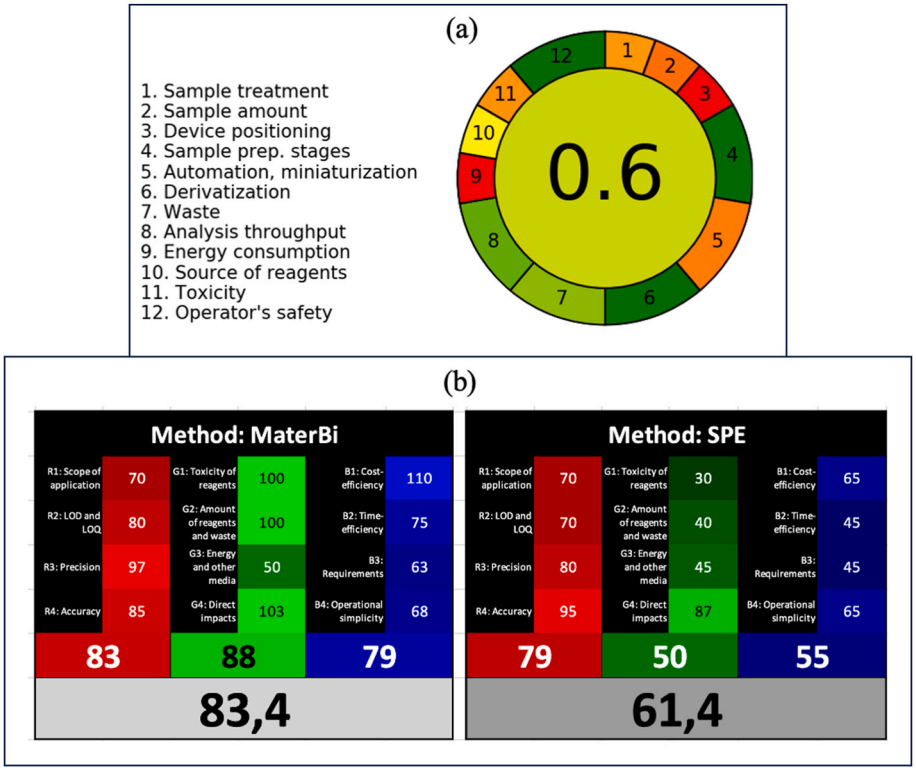

Fig. 6. Scores obtained for the present method by the application of (a) the AGREE software and (b) the RGB algorithm. In this latter case, a reference SPE method developed in our laboratory was used for comparison.

3.7. Application to real samples

The method was applied to thirteen WWTP samples, to test its applicability in determining the considered emerging contaminants. The samples consisted of water collected after the secondary treatment of an Italian WWTP, in autumn 2023. Most analytes were detected in the more diluted samples (preconcentration factor = 1.33), thus allowing external calibration. The detection of UV filters required the analysis of the 20-fold preconcentrated samples, but correction for ME was necessary in few cases.

The results of the analysis are shown in Table S7 (SM) and graphically represented by the principal component analysis (PCA) in Fig. S7. Among pharmaceuticals, NSAIDs and FRSM were detected in all samples, at concentrations ranging from 0.007 to 8 μg L^{-1}. The most concentrated analytes were KET, NAP and IBU, with particularly high values in C4 and C6, which resulted highly correlated in the PCA. DCF showed a relatively high concentration in all samples as well, with quite constant values (average for the 13 samples equal to 0.6 ± 0.2 μg L^{-1}). On the other hand, GEM was below the LOD in 4 samples, and generally at lower concentrations, compared to the other pharmaceuticals. The UV-filters BP-3 and OD-PABA were always detected, with levels of approximately 40–50 and 5–14 ng L^{-1}, respectively. Slightly higher concentrations, up to 430 ng L^{-1}, were observed for EHMC, but in fewer samples (levels below LOQ in half of them). EHS was always detected below LOQ, while OC was below LOD in 3 samples and below LOQ in all the other samples, except for C2. This was also the only sample in which BPA was quantifiable. Finally, estrogens and TCS were mostly below LOD, except for E2 in sample C4 and TCS in sample C5, where concentrations close to the LOQ were observed for both analytes.

Even though lower LODs could be reached by using higher preconcentration factors, the detection of all the validated analytes in most samples demonstrates the suitability of the method for this application.

As a final remark, it is worth noting that, even if PFOA and PFOS were not quantitively extracted by the developed procedure, they were detected in all analysed samples.

The presence of the 18 emerging contaminants in all samples demonstrates once again that the conventional wastewater treatment is not suitable to remove many current pollutants, as previously reported [55].

4. Conclusions

A first investigation of the analytical capability of the biodegradable polymer Mater-bi was herein presented for the determination of emerging contaminants in water. Since the exact composition is not disclosed, its sorption capabilities were explored for a wide range of compounds, for the first time.

The results of the multivariate optimization on the extraction of 39 analytes of different chemical properties, highlighted a favoured and satisfactory interaction of the material only with the hydrophobic and acidic analytes, under specific conditions. By also studying the kinetics of the uptake, a final FPSE-type method was proposed for the exhaustive extraction of 16 analytes, including pharmaceuticals, UV filters, BPA, estrogens and triclosan.

The developed final method involves an overall rapid, extremely inexpensive and safe sample preparation, complying with the main principles of green analytical chemistry. The method also demonstrated very good performances, being accurate, precise, multi-analyte, highly specific and characterized by negligible matrix effect. The biodegradable characteristic of the material allows to reduce waste in this novel sample preparation strategy, enhancing sustainability.

The Mater-Bi film was particularly suitable for the extraction of mainly hydrophobic compounds. Still, future studies may focus on perfluorinated compounds, since PFOA and PFOS showed a certain affinity for the material. The future application to other sample types and/or other analytes seems promising, upon careful optimization.

CRediT authorship contribution statement

Barbara Benedetti: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Erica Ceccardi:** Visualization, Validation, Investigation, Formal analysis, Data curation. **Henry MacKeown:** Writing – review & editing, Investigation, Data curation. **Marina Di Carro:** Writing – review & editing, Supervision, Resources. **Emanuele Magi:** Writing – review & editing, Supervision, Resources.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aca.2024.342725.

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