Producing Magnetic Nanocomposites from Paper Sludge for the Adsorptive Removal of Pharmaceuticals from Water—A Fractional Factorial Design

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Abstract: In view of a simple after-use separation, the potentiality of producing magnetic activated carbon (MAC) by intercalation of ferromagnetic metal oxide nanoparticles in the framework of a powder activated carbon (PAC) produced from primary paper sludge was explored in this work. The synthesis conditions to produce cost effective and efficient MACs for the adsorptive removal of pharmaceuticals (amoxicillin, carbamazepine, and diclofenac) from aqueous media were evaluated. For this purpose, a fractional factorial design (FFD) was applied to assess the effect of the most significant variables (Fe3+- to Fe2+ salts ratio, PAC to iron salts ratio, temperature, and pH), on the following responses concerning the resulting MACs: Specific surface area (S_{BET}), saturation magnetization (M_s), and adsorption percentage of amoxicillin, carbamazepine, and diclofenac. The statistical analysis revealed that the PAC to iron salts mass ratio was the main factor affecting the considered responses. A quadratic linear regression model A = f(S_{BET}, M_s) was adjusted to the FFD data, allowing to differentiate four of the eighteen MACs produced. These MACs were distinguished by being easily recovered from aqueous phase using a permanent magnet (M_s of 22–27 emu g⁻¹), and their high S_{BET} (741–795 m² g⁻¹) were responsible for individual adsorption percentages ranging between 61% and 84% using small MAC doses (35 mg L⁻¹).

Keywords: activated carbon; adsorption; aquatic environment; emerging contaminants; micro-organic contaminants; magnetic materials; multivariate analysis

1. Introduction

Over the past decade, pharmaceuticals have been recognized as potential toxic environmental contaminants and, as a result, their occurrence in aquatic environments gained considerable attention worldwide. Resulting from their massive consumption, substantial amounts of pharmaceuticals in both their unchanged and metabolized forms are directly or indirectly discarded into aquatic systems. Therefore, concentration levels of ng L⁻¹ to μg L⁻¹ can be commonly found in surface water and groundwater [1–3] and some studies have even reported the occurrence of pharmaceuticals at mg L⁻¹ levels [4,5]. Given the detected values and due to their persistence in natural waters, pharmaceuticals pose a long-term menace to aquatic organisms and can induce undesirable effects on both humans and ecosystems [1,2,6,7]. In order to address emerging concern regarding the contamination by pharmaceuticals, Directive 2013/39 EU set the necessity of studying their environmental risks and of protecting the aquatic environment and human health, simultaneously highlighting that the development of innovative cost effective water treatment technologies should be stimulated [8].
Several approaches have been investigated for the removal of pharmaceuticals from waters (e.g., biological treatments, reverse osmosis, nanofiltration, ozonation, and advanced oxidation processes) [9]. Among them, adsorption is a well-researched technique, and its recognition lies in the low initial investment needed, the operational simplicity and its versatility [1]. Carbonaceous adsorbents, in particular powdered activated carbon (PAC), are usually preferred for the adsorptive removal of pharmaceuticals from waters, due to their porous structure and their high specific surface area ($S_{BET}$) [1,10,11]. The production of PAC using industrial and agricultural wastes as precursors has been focus of special attention, in a way to increase the sustainability of these carbon materials [10]. Pulp and paper mill sludge is an example of a widely produced waste (50 kg of dry sludge per tonne of paper), which economic and sustainable management is a continuous challenge for the industry. Given the cellulosic nature of this residue, it presents the adequate properties to be used as precursor of carbonaceous adsorbents. In this sense, the application of paper mill sludge-derived adsorbents for water remediation has been explored by several authors regarding the removal of pharmaceuticals [12–15], and other organic [16,17] and inorganic [18] contaminants from waters. Along with the use of alternative precursors, aiming to generalize the application and increase the potential of carbonaceous adsorbents, a lot of research work has been devoted to their structural and chemical modification. In the last decade, the anchorage of ferromagnetic metal oxides (e.g., iron oxides) on its carbon matrix has arisen as a suitable solution to overcome difficulties in the after-use separation of PAC [19,20]. The inclusion of magnetic nanoparticles on PAC allows for the recovery of the adsorbent using an external magnetic field, so avoiding the filtration and/or centrifugation operations usually needed for PAC separation. In this way, the use of magnetic activated carbon (MAC) reduces the overall process cost and complexity [20,21].

Different synthesis routes can be used to produce MAC (e.g., co-precipitation, oxidative hydrolysis of ferrous salts, thermochemical and mechanical treatments), but co-precipitation is typically the selected method, owing to its low cost and simplicity [20,22]. The magnetically active components usually introduced in PAC framework by co-precipitation are magnetite ($Fe_3O_4$) and maghemite ($\gamma-Fe_2O_3$). Anyhow, the magnetic, textural and morphologic properties imparted to MAC are highly dependent on the concentration of ferric ($Fe^{3+}$) and/or ferrous ($Fe^{2+}$) salts, the alkaline conditions (concentration of OH$^-$) [23], the synthesis temperature [23,24] used to produce iron nanoparticles and also the ratio between PAC and iron salts [25]. Therefore, the management of the above-mentioned experimental parameters has been shown to be crucial to achieve the desired features in terms of size and distribution of nanoparticles [24,26], magnetic properties (saturation magnetization, $M_s$) and $S_{BET}$ of the materials [27]. However, to the best of our knowledge, the combined effect of these synthesis conditions and their impact on the features and adsorptive performance of waste-based MACs have not been assessed yet.

The aim of this work was to determine the conditions to produce efficient magnet-responsive nanocomposite materials by in-situ iron oxide co-precipitation onto PAC prepared from paper mill sludge for application in the adsorption of pharmaceuticals from water. For that purpose, a fractional factorial design (FFD) was employed to evaluate the effect of production variables ($Fe^{3+}$:$Fe^{2+}$ molar ratio, PAC:Fe salts mass ratio, reaction temperature, and pH conditions) on the properties ($S_{BET}$ and $M_s$) and adsorptive performance (pharmaceutical percentage of adsorption, $A$) of the resulting waste-based MACs. For the latter, pharmaceuticals from three different therapeutic classes, namely amoxicillin (AMX, antibiotic), carbamazepine (CBZ, antiepileptic), and sodium diclofenac (DCF, non-steroidal anti-inflammatory drug) were selected as adsorbate models. After selecting the most appropriate production conditions, the morphology, composition and surface structure of the selected MACs were assessed by scanning electron microscopy (SEM), X-ray fluorescence (XRF), and X-ray photoelectron spectroscopy (XPS) analyses, respectively.
2. Materials and Methods

2.1. Reagents and Chemicals

The reagents used in the present work were of analytical grade. Potassium hydroxide (KOH, LABCHEM, ≥86%) was used in the chemical activation of primary paper mill sludge and in the synthesis of MAC by the co-precipitation method. Hydrochloric acid (HCl, AnalaR NORMAPUR, 37%) was used in the washing process of PAC. Ferric chloride hexahydrate (FeCl₃·6H₂O, >99%) and ferrous sulphate heptahydrate (FeSO₄·7H₂O, >99%) were purchased from Chem-Lab. The buffer solutions used for the pH meter calibration, with pH values of 4.01 ± 0.01, 7.01 ± 0.01, and 10.1 ± 0.01, were acquired from Hanna Instruments. The pH adjustments were performed using a solution of ca. 0.5 mol L⁻¹ KOH. Adsorption studies were performed with three pharmaceuticals: Carbamazepine (C₁₂H₁₂N₂O 99%, Sigma-Aldrich, St. Louis, MS, USA–EUA), sodium diclofenac salt (C₁₄H₁₀Cl₂Na₂O₂, TCI, >98%) and amoxicillin tri-hydrate (C₁₆H₂₆N₃O₉S > 98%, TCI, Tokyo-Japan). The chemical structures and physico-chemical properties of these pharmaceuticals are depicted in Table S1 of Supplementary Materials. For micellar electrokinetic chromatography (MEKC) analyses, the following reagents were used: Hexadimethrine bromide ((C₁₃H₃₀Br₂N₂)₂, 95%, Sigma) for capillary coating, ethylvanillin (C₉H₆OC₆H₃(OH)CHO 99%, Sigma-Aldrich,) as internal standard, and sodium tetraborate decahydrate (Na₂B₄O₇·10H₂O, Riedel-de-Haën, Seelze–Germany) and sodium dodecyl sulfate (CH₃(CH₂)₁₁·OSO₃Na, Pan-Reac, PA-ACS, Barcelona, Spain) as separation buffer. All solutions were prepared in ultrapure water (18.2 MΩ cm⁻¹, PURELAB flex 4 system, ELGA VEOLIA, High Wycombe, UK).

2.2. Preparation of Powdered Activated Carbon

Primary sludge (PS) from pulp and paper mill industry was used as precursor to prepare PAC, according to the optimized experimental conditions determined by Jaria et al. (2019) [28]. PS was collected from a pulp and paper mill that employs the kraft elemental chlorine free production process and uses eucalyptus (Eucalyptus globulus) wood. Briefly, PS was first impregnated with KOH activating agent using a 1:1 w/w ratio (batches of 15 g of PS with 15 g of KOH in 50 mL of distilled water), under ultrasonic stirring for 1 h and left to dry at room temperature in a laboratory fume hood. The dried material was then pyrolyzed in porcelain crucibles at 800 °C in a muffle for 150 min (heating rate of 10 °C min⁻¹), under N₂ atmosphere. The carbonized material was washed with 1.0 M HCl (for ashes and KOH removal) and distilled water (until neutral pH of the leachate was reached) and dried overnight at 100 °C. Finally, the material was crushed in order to obtain a fine homogenous powder [28].

2.3. Preparation of Magnetic Activated Carbon

The loading of iron oxide magnetic nanoparticles onto PAC to produce MACs was performed by co-precipitation. The magnetic nanoparticles were synthesized by alkaline co-precipitation of FeCl₃·6H₂O and FeSO₄·7H₂O salts, and to avoid the formation of non-magnetic forms of iron oxides, the reaction was conducted in inert atmosphere. The systematic synthesis of MACs is described according to the following procedure. Firstly, the ultrapure water used in the synthesis was degassed for 30 min with N₂ to prevent from oxidation of iron salt solutions prior to MAC synthesis. A solution containing both FeCl₃·6H₂O (concentration interval between 0.022–0.073 mol L⁻¹) and FeSO₄·7H₂O (concentration interval between 0.037–0.087 mol L⁻¹) salts was prepared (for a total volume of 50 mL) and transferred to a glass reactor (during this step no color alteration was observed, nor the formation of a precipitate), followed by the addition of the PAC prepared in Section 2.2. The mixture was then heated to a pre-defined temperature, under oxygen-free conditions (N₂ flow) and stirred at 100 rpm. These conditions were kept during the whole operation. A KOH solution (~0.5 mol L⁻¹) was added dropwise (for a volume varying between 39 mL and 50 mL) to achieve the desired pH and the reaction was held for 1 h, keeping the defined temperature. After magnetic decantation, the supernatant (excess of alkali solution) was discarded, and the produced MACs were thoroughly washed with.
distilled water until neutral pH of the washing leachate was reached. The materials were then dried at 50 °C for 48 h, mechanically grinded and finally stored in a sealed container prior to their use. A total of 18 MAC materials were produced and the experimental conditions used, i.e., molar ratio between FeCl$_3$·6H$_2$O and FeSO$_4$·7H$_2$O salts (Fe$^{3+}$:Fe$^{2+}$), mass ratio between PAC and iron salts (PAC:Fe), reaction temperature and pH conditions, are summarized in Table 1.

**Table 1.** Experimental conditions (Fe$^{3+}$:Fe$^{2+}$ molar ratio, PAC:Fe mass ratio, reaction temperature and pH conditions), their codified variables and factor levels of the fractional factorial design (FFD) applied to optimize the production of the 18 magnetic activated carbons (MACs).

| Factors          | MAC | Fe$^{3+}$:Fe$^{2+}$ ($x_1$) | PAC:Fe ($x_2$) | Temperature ($x_3$) | pH ($x_4$) |
|------------------|-----|---------------------------|---------------|--------------------|------------|
|                  |     | Molar Ratio Level | Mass Ratio Level | °C Level | pH Level |
| 1                | 1:6 | −1 | 1:3 | 60 | 0 |
| 2                | 1:6 | −1 | 1:4 | 60 | 0 |
| 3                | 1:6 | −1 | 1:6 | 80 | 1 |
| 4                | 1:6 | −1 | 1:3 | 80 | 1 |
| 5                | 1:6 | −1 | 1:4 | 40 | −1 |
| 6                | 1:6 | −1 | 1:6 | 40 | −1 |
| 7                | 1:6 | −1 | 1:3 | 80 | 1 |
| 8                | 1:6 | −1 | 1:4 | 40 | −1 |
| 9                | 1:6 | −1 | 1:6 | 40 | −1 |
| 10               | 1:6 | −1 | 1:3 | 40 | −1 |
| 11               | 1:6 | −1 | 1:4 | 40 | −1 |
| 12               | 1:6 | −1 | 1:6 | 80 | 1 |
| 13               | 1:6 | −1 | 1:3 | 40 | −1 |
| 14               | 1:6 | −1 | 1:4 | 40 | −1 |
| 15               | 1:6 | −1 | 1:6 | 60 | 0 |
| 16               | 1:6 | −1 | 1:3 | 60 | 0 |
| 17               | 1:6 | −1 | 1:4 | 80 | 1 |
| 18               | 1:6 | −1 | 1:6 | 60 | 0 |

2.4. Process Variables and Experimental Fractional Factorial Design

An experimental fractional factorial design (FFD) (relationship between input factors (variables) and output effects (responses) in a process) was used to determine the optimum set of operational variables to produce MAC materials, since it allows to perform a systematic optimization of the process with a reduced number of experiments and depletion of resources.

2.4.1. Factors

The process variables in the procedure above described (Section 2.3) for the production of MACs were: Molar ratio between FeCl$_3$·6H$_2$O and FeSO$_4$·7H$_2$O salts (Fe$^{3+}$:Fe$^{2+}$), mass ratio between PAC and iron salts (PAC:Fe), reaction temperature and pH conditions, for which the considered values are depicted in Table 1. The test hypothesis was to investigate if each one of the referred variables had a significant impact on the characteristics and adsorptive performance of the resulting MAC (see Section 2.4.2 for selected responses). The variables and corresponding tested levels were chosen according to previous work of the group and other literature studies where such conditions were applied in an individual approach and not in a systematized way, hindering the possibility of a statistical analysis. Specifically, studies by Ilbay et al. (2015) [29], Wong et al. (2016) [30], Badi et al. (2018) [26], Rai and Singh (2018) [19], and Lompe et al. (2018) [27] applied synthesis temperatures ranging from room temperature to 80 °C; Arya and Philip (2016) [31], Danaloğlu et al. (2017) [32] and Rai and Singh (2018) [19] performed the MAC synthesis at pH ranging
from 8 to 12; \( \text{Fe}^{3+} : \text{Fe}^{2+} (w/w) \) salts ratio from 3.2:1 to 0.5:1 were explored by Castro et al. (2009) [33], Ilbay et al. (2015) [29], Danalioğlu et al. (2017) [32], Badi et al. (2018) [26] and Pereira et al. (2020) [15]; and PAC:Fe salts \((w/w)\) ratio between 1:2 and 1:6 were addressed by Ilbay et al. (2015) [29] and Pereira et al. (2020) [15].

The FFD design matrix was obtained by codifying the studied factors, i.e., \( \text{Fe}^{3+} : \text{Fe}^{2+} \) molar ratio \((\chi_1)\), PAC:Fe salts mass ratio \((\chi_2)\), reaction temperature \((\chi_3)\) and pH \((\chi_4)\), as follows. The optimization of the MAC synthesis was performed using a fractional design with mixed levels: Three factors \((\chi_1, \chi_2 \text{ and } \chi_3)\) at three levels \((3^3-1)\) and a two-level factor \((\chi_4)\). A total of eighteen MACs were produced according to the planned FFD \((N = 3^3-1 \times 2)\). Each factor, when three levels are to be considered, is assigned to “low,” “medium” and “high,” being denoted as \(-1, 0, \text{ and } +1\), respectively, or “low” and “high” when only two levels are applied, as described in Table 1.

### 2.4.2. Responses

The magnitude and the direction of the factor effects on the response modelling were evaluated, using the following responses: \( S_{\text{BET}}, M_s \) and percentage of adsorption of AMX, CBZ and DCF from aqueous solutions \((A)\).

#### (i) Specific surface area

The \( S_{\text{BET}} \) of MACs was determined by \( N_2 \) adsorption isotherms at \(-196 \, ^\circ\text{C}\) using a Micromeritics Instrument, Gemini VII 2380, after outgassing the materials overnight at 120 \( ^\circ\text{C} \). The \( S_{\text{BET}} \) was calculated by means of Brunauer–Emmett–Teller equation [34] in the relative pressure range between 0.01 and 0.1. The \( N_2 \) adsorption isotherms obtained for PAC and selected MACs from the FFD (MAC 4, MAC 7, MAC 11, and MAC 17) are presented in Figure S1, as Supplementary Materials. Additionally, the total micropore volume \((V_{\text{mic}})\), the total pore volume \((V_p)\) and average pore width \((D)\) were also determined. \( V_{\text{mic}} \) was determined by the Dubinin–Radushkevich equation [35], as for \( V_p \), this parameter was estimated from the amount of \( N_2 \) adsorbed at a relative pressure of 0.99 and \( D \) was determined by using the following equation [12]:

\[
D = 2 \times V_p/S_{\text{BET}}
\]

The pore size distribution was determined by Non-Local Density Functional Theory (NLDFT) analysis assuming slit pores.

#### (ii) Saturation magnetization

The magnetization measurements were conducted in a vibrating sample magnetometer (VSM EV9), with an applied magnetic field to a maximum of 22 kOe. By plotting the magnetic moment as a function of the applied magnetic field, it is possible to determine the \( M_s \) of each MAC, dividing the plateau found for the magnetic moment by the MAC mass \( (10 \, \text{mg}) \). Prior to the analysis, the instrument was calibrated with a disk of pure nickel and applying a magnetic field of c.a.1 Oe and with dispersion on the magnetic moment inferior to 0.5%.

#### (iii) Adsorption percentage

Individual solutions of AMX, CBZ and DCF with an initial concentration \((C_i)\) of 5 mg L\(^{-1}\) were prepared by dissolving a specific amount of each pharmaceutical in ultrapure water. Batch adsorption experiments were conducted in 50 mL polypropylene falcon tubes, into which were put into contact 40 mL of pharmaceutical solution (AMX, CBZ, or DCF, with no pH adjustment) with 1.4 mg of the corresponding MAC (dose of 35 mg L\(^{-1}\)). Then, falcon tubes were shaken for 4 h (preliminary experiments with different MACs showed that such a contact time guarantees a situation of equilibrium) in an overhead shaker (Heidolph, Schwabach–Germany, Reax 2) at 80 rpm under controlled room temperature (25.0 \( \pm \) 0.1 \( ^\circ\text{C} \)). After shaking during the defined time, the solutions were collected and filtered through 0.22 \( \mu\text{m} \) PVDF filters (Whatman) for the analytic determination of the remaining pharmaceutical concentration \((C_f)\). The analytic quantification of AMX, CBZ,
and DCF was performed by micellar electrokinetic chromatography (MEKC), according to the procedure described in Section 2.5. Blank controls containing each pharmaceutical (C_i of 5 mg L^{-1} and without any MAC) were shaken during the same time as the adsorption experiments and used as reference for the calculation of adsorption percentages (A) for each pharmaceutical, using Equation (2):

\[ A = \frac{C_0 - C_f}{C_0} \times 100 \]  

(2)

where C_i (mg L^{-1}) is the remaining pharmaceutical concentration in the liquid phase of adsorption experiments at the end of shaking and C_0 (mg L^{-1}) is the concentration of pharmaceutical in the corresponding control experiments.

2.5. Analytic Quantification of Pharmaceuticals

The quantification of the pharmaceuticals in the aqueous solutions was carried out by MEKC, using a Beckman P/ACE MDQ (Fullerton, CA, USA) instrument, equipped with a UV-visible detection system. A silica capillary was dynamically coated according to the procedure described by Calisto et al. (2011) [36]. The electrophoretic separation was performed by direct polarity mode at 25 kV and 25 °C, during 2.5 min for AMX and DCF and during 3.0 min for CBZ. All samples and standard solutions were spiked with the internal standard ethylvanillin (final concentration of 3.34 mg L^{-1}). The detection was monitored at 200 nm for DCF and AMX and 214 nm for CBZ. The separation buffer used was composed by 15 mmol L^{-1} of sodium tetraborate and 30 mmol L^{-1} of SDS for CBZ and AMX, and 15 mmol L^{-1} of sodium tetraborate and 50 mmol L^{-1} of SDS for DCF; the separation buffer was renewed every six runs. After each run, the capillary was washed with ultrapure water (60 s) and then with the separation buffer (90 s), at 20 psi. The determination of the calibration curve was carried out for each pharmaceutical using seven standard solutions with concentrations ranging between 0.500 mg L^{-1} and 5.00 mg L^{-1}.

All the analyses were performed in triplicate. The detection limit of the method (3σ), within the concentration range used, was 0.307 mg L^{-1}, 0.263 mg L^{-1} and 0.289 mg L^{-1} for AMX, CBZ, and DCF, respectively.

2.6. Data Treatment

Analysis of variance (ANOVA) of the FFD results was applied to evaluate the significance of each experimental variable (\chi_1, \chi_2, \chi_3, and \chi_4) tested in the selected responses (S_{BET}, M_s, A_{AMX}, A_{CBZ}, and A_{DCF}). The p-values were used as a tool to check the significance of each factor on the obtained responses, with a confidence level of 95% (p-values ≤ 0.05 indicated significant factors, while p-values > 0.05 indicated non-significant factors).

Furthermore, principal component analysis (PCA) and hierarchical cluster analysis (HCA) using centroid linkage method and Euclidean metric, were applied to the same data to identify patterns among the different MACs. Additionally, and using the loadings of the PC1 corresponding to the columns of the adsorption of AMX, CBZ, and DCF, an overall adsorption removal was defined, A_{pooled} (%), which was calculated by means of Equation (3):

\[ A_{pooled} = 0.5294A_{AMX} + 0.5923A_{CBZ} + 0.6073A_{DCF} \]  

(3)

Also, a linear quadratic model of A_{pooled} versus S_{BET} and M_s was fitted and used to assess the optimal MAC regarding adsorption performance.

Matlab software R2019a (The MathWorks, Co., Natick, MA, USA) was used for all calculations and graphs.

2.7. Morphological and Chemical Characterization of Selected Materials

Materials selected from the previous FFD (based on the data analysis of Section 3.3) were further characterized, namely by the determination of the morphological and chemical composition. The morphological features of the selected MACs were evaluated by scanning
electron microscopy (SEM) using a S4100 Hitachi (Tokyo, Japan) equipment and an electron acceleration voltage of 20 kV. Prior to the analysis, the samples were coated with a thin film of amorphous carbon. The following magnifications were used: 500×, 3000×, and 10,000×. The chemical composition on the MACs surface was determined by X-ray diffraction (XRD), X-ray fluorescence (XRF), and X-ray photoelectron spectroscopy (XPS). XRD measurements were performed at room temperature with a PANalytical Empyrean powder diffractometer using monochromated CuKα radiation (λ = 1.5418 Å) in the 2θ range at 0.02° resolution, and 4000 acquisition points per step. The XRD analysis was performed using a Malvern Panalytical Aztec spectrometer, under inert atmosphere (He) and applying a maximum voltage of 36.50 kV and 60 kV and a maximum current of 60 mA, 72 mA and 100 mA. The XPS spectra of the selected MACs were acquired in an Ultra High Vacuum (UHV) system using monochromated AlKα (1486.74 eV) X-ray source. High-resolution spectra were recorded at a normal emission take-off angle and with a pass-energy of 20 eV, which provides an overall instrumental peak broadening of 0.5 eV.

3. Results and Discussion
3.1. Fractional Factorial Design

The responses assessed in the FFD analysis, namely \( S_{BET} \), \( M_s \) and \( A \) for each of the considered pharmaceuticals, are shown in Figure 1 for the eighteen produced MACs.

Regarding the structural properties of the eighteen produced MACs, the \( S_{BET} \) ranged between 475 m\(^2\) g\(^{-1}\) and 899 m\(^2\) g\(^{-1}\), being these values lower than that obtained for the bare PAC (1438 m\(^2\) g\(^{-1}\)). Still, \( S_{BET} \) of the here produced MACs are similar or even higher than most of values determined for waste-based magnetic carbons in the literature [22,37]. The lower \( S_{BET} \) of MACs when compared with PAC can be explained by the decrease and/or blockage of pores on PAC framework by the iron oxide nanoparticles produced by co-precipitation [27,38,39], and also by the very small fraction of PAC to iron salts (factor \( \chi_1 \)) and maintaining constant the Fe\(^{3+}:Fe^{2+} \) molar ratio (factor \( \chi_2 \)), \( S_{BET} \) decreases and consequently, \( M_s \) increases (e.g., MAC 1 to 3, MAC 13 to 15, and MAC 16 to 18).

This trend was also evidenced by other authors and was explained by the increase on the amount of magnetic iron oxide nanoparticles onto the AC framework [27,41,42].
However, this tendency was not shown by the remaining set of MAC materials (MAC 5 to 7, MAC 7 to 9 and MAC 10 to 12), probably because they are also affected by the temperature and pH of the reaction medium, also considered as variables in the synthesis of MACs.

![Figure 1. Values obtained for $S_{BET}$ (A), $M_s$ (B) and $A$ of AMX, CBZ and DCF (C) for the 18 produced MACs. The line draw in (B) corresponds to the minimum $M_s$ value (16 emu g$^{-1}$) that assures an effective magnetic separation, according to [40].](image)

MAC 16 ($\chi_1$ of 2:1 $w/w$, $\chi_2$ of 1:3 molar ratio, $\chi_3$ of 60 °C and $\chi_4$ of 13.5), which was the material that presented the highest $S_{BET}$ (899 m$^2$ g$^{-1}$), also displayed the highest adsorption efficiencies for all the pharmaceuticals (Figure 1C), with percentages of adsorption...
of (76.6 ± 4.5)% for AMX, (76.7 ± 5.8)% for CBZ and (85.5 ± 3.9)% for DCF. Despite these results, the low $M_s$ of MAC 16 (6.2 emu g$^{-1}$) resulted in a weak magnetic separation and recovery of the material from solution. On the other hand, MAC 15 presented a $M_s$ of 44 emu g$^{-1}$, which assures a fast and effective magnetic separation from aqueous media, but a relatively low $S_{\text{BET}}$ (539 m$^2$ g$^{-1}$) that negatively affected the adsorptive performance of this material, with adsorption efficiencies of (45.5 ± 4.1)% for AMX, (39.5 ± 5.3)% for CBZ and (37.1 ± 4.7)% for DCF. Preliminary experiments showed that the bare magnetic iron oxide nanoparticles have almost no adsorption affinity towards these pharmaceuticals, and as for PAC, the adsorption of these three contaminants was almost complete (>95%).

3.2. Statistical Data Analysis

3.2.1. Analysis of Variance

To evaluate the effects of the process factors on the studied responses, allowing for a more systematic analysis of the results, an ANOVA statistical analysis was performed, and the obtained results are depicted in Table S3 in Supplementary Materials.

The $p$-values above 0.05 obtained for Fe$^{3+}$:Fe$^{2+}$ molar ratio ($\chi_1$), reaction temperature ($\chi_3$) and reaction pH ($\chi_4$) suggest that none of these factors has a significant effect on the responses. For the factor $\chi_2$, the $p$-values below 0.05 (identified in bold in Table S3) attained for $S_{\text{BET}}$ and $M_s$ clearly indicate the effect of the mass ratio between PAC and iron salts used in the synthesis of MACs on both responses. Such an effect may be visualized in the relationship graphical representations displayed in Figure S3, as Supplementary Materials. The important role of the PAC:Fe ratio is in agreement with some previous studies, which refer the mass ratio between the carbonaceous precursor and the iron salts as one of the experimental conditions affecting the magnetic and structural properties of MACs produced by co-precipitation [27,41]. Moreover, the adsorption percentage of CBZ and DCF is also influenced by factor $\chi_2$ ($p$-values ≤ 0.05), and since the adsorptive removal of pharmaceuticals from aqueous solutions generally depends on and is positively correlated with $S_{\text{BET}}$, this behavior was somehow expected [25,27,42]. This was not the case for AMX adsorption, since the $p$-values > 0.05 obtained from the ANOVA analysis point that the variables tested in the synthesis of MAC did not markedly affect this response.

To identify patterns in the obtained responses, highlighting similarities and differences and allowing for the grouping of MACs, PCA and HCA analyses were performed, with the obtained results being shown in Figure 2. The score graph of the first two principal components (PC1 and PC2) explained a cumulative proportion of the data variance of 84.7%, corresponding to 73.0% and 11.7% respectively for PC1 and PC2 (Figure 2A). It is evident that $M_s$ and $S_{\text{BET}}$ values of the produced MAC follow opposite trends, which is related to the decrease in $S_{\text{BET}}$ values resultant from the incorporation of the magnetic iron oxides nanoparticles in the carbonaceous framework (further information in Section 3.3). The adsorption percentages of CBZ and DCF and $S_{\text{BET}}$ are grouped in the same quadrant, which reflects a strong and usually positive correlation between these responses. As for the adsorption of AMX, no correlation with the other responses was observed. However, other factors, namely the surface chemistry of MACs and the characteristics inherent to each pharmaceutical, have an important role in the removal efficiency. This might be a possible explanation for the fact that an increment in $S_{\text{BET}}$ not always imply an increase in the adsorption percentage and the absence of correlation between $A_{\text{AMX}}$ and the other responses.

From the PCA plot (Figure 2A) and according to the dendrogram of the HCA results using centroid linkage method and Euclidean metric (Figure 2B), five distinct clusters can be defined. Two groups presenting distinct and opposite $M_s$ and $S_{\text{BET}}$ values can be identified, the first one including MAC 15, MAC 12, and MAC 9 (group 1) and the second one, MAC 16 (group 2). Group 1 is characterized by MACs with the highest $M_s$, with values varying between 37.2 emu g$^{-1}$ and 44.2 emu g$^{-1}$, the high amount of iron oxide magnetic nanoparticles dispersed on the PAC structure resulting in relatively low $S_{\text{BET}}$, in particular for MAC 15 and MAC 12. Due to these low $S_{\text{BET}}$ values, MAC 15, MAC 12, and MAC 9 exhibited the lowest adsorption percentages for AMX (between 37%
and 44%), CBZ (between 40% and 48%) and DCF (between 46% and 59%). Group 2 is comprised solely by MAC 16, which has the highest $S_{BET}$ value, and consequently the highest adsorption percentages towards AMX (65% to 76%), CBZ (67% to 77%) and DCF (between 84% and 86%). Three additional groups can be defined in the PCA biplot: Group 3 (MAC 1, MAC 4, MAC 7, MAC 11, MAC 13, and MAC 17), group 4 (MAC 2, MAC 5, MAC 10, and MAC 18) and group 5 (MAC 3, MAC 6, MAC 8, and MAC 14), most of them characterized by having intermediate values of $M_s$ and $S_{BET}$ and satisfactory $A$ values towards the studied pharmaceuticals. Based on this overall analysis, MAC 4, MAC 11, and MAC 17 (sub-category of group 3) and MAC 2, MAC 5, and MAC 18 (sub-category of group 4) may be selected as appropriate materials for application in the adsorptive removal of pharmaceuticals, all of them having reasonably good responses ($S_{BET} > 640 \text{ m}^2 \text{ g}^{-1}$, $M_s > 20 \text{ emu g}^{-1}$ and $A > 50\%$ for either AMX, CBZ or DFC, as shown in Figure 1).

3.2.2. Quadratic Regression

In order to find the optimal MACs regarding adsorption performance, a quadratic linear regression model relating a weighted average of the adsorption of the three pharmaceuticals as a function of $M_s$ and $S_{BET}$ was fitted. The weights of each pharmaceutical are

![Figure 2. PCA score graph (A) and dendrogram of the hierarchical cluster analysis (HCA) results using centroid linkage method and Euclidean metric (B) of the eighteen MAC materials.](image-url)
the components of the first eigenvector, i.e., the first principal component PC1 (73.0%). Equation (4) describes the relation between $A_{\text{pooled}}$, $M_s$, and the overall adsorption removal ($A_{\text{pooled}}$, calculated using Equation (3)), with a satisfactory correlation coefficient $R^2$ of 0.891:

$$A_{\text{pooled}} = 1.53 \times 10^{-4} S_{\text{BET}}^2 - 5.84 \times 10^{-2} M_s^2 - 3.05 \times 10^{-3} S_{\text{BET}} M_s + 4.26 M_s - 5.58 \times 10^{-2} S_{\text{BET}} + 6.16 \times 10^1 \quad (4)$$

From the 3D graphical representation of the three responses ($S_{\text{BET}}, M_s$, and $A_{\text{pooled}}$), which is depicted in Figure 3, it is clear a positive correlation between $A_{\text{pooled}}$ and $S_{\text{BET}}$, and also that higher $S_{\text{BET}}$ values typically result in MACs with lower $M_s$, and vice-versa. This information corroborates the results from the PCA analysis, in which MAC 12 and MAC 15, and MAC 16 and MAC 13, present opposite trends regarding the $M_s$ magnetic properties and both $S_{\text{BET}}$ and $A_{\text{pooled}}$.

**Figure 3.** Three-dimensional plot of the three responses for the eighteen MAC materials.

Furthermore, based on this 3D graphical representation, it was possible to observe that MAC 4 and MAC 7 ($\chi_2$ of 1:3 and $\chi_4$ of 9.5) and MAC 11 and MAC 17 ($\chi_2$ of 1:4 and $\chi_4$ of 13.5), are the materials that gather the best compromise between magnetic properties and binding capacity towards the pharmaceuticals from different classes here considered. For these MAC, the $M_s$ values ranged between 22 emu g$^{-1}$ and 27 emu g$^{-1}$, allowing their efficient separation from aqueous media, and the values of $S_{\text{BET}}$ ranging between 741 m$^2$ g$^{-1}$ and 795 m$^2$ g$^{-1}$ were quite satisfactory, allowing the adsorption of 61% to 70%, 69% to 77%, and 80% to 84% for AMX, CBZ, and DCF, respectively.

### 3.3. Morphologic and Chemical Features of the Optimal MAC

The morphologic features of MAC 4, MAC 7, MAC 11, and MAC 17 were evaluated by SEM, with the obtained images being represented in Figure 4. The micrographs of these four materials show small iron oxide nanoparticles of different shapes and sizes, distributed onto the surface of PAC. Besides that, it is clear from these images that the pores of the carbonaceous matrix of PAC are partially obstructed/blocked by the magnetic nanoparticles (see Figure S4, as SM) and this explains the decrease observed in both total pore volume (between 24% to 37%) and micropore volume (between 45% to 50%), and consequently in the $S_{\text{BET}}$ values of these materials. Still, the SEM images of these MACs revealed the formation of well-developed porous structures, with the micropore volume accounting for ca. 39% to 46% of the total pore volume (according with the $S_{\text{BET}}$ data provided in Table S2).
and binding capacity towards the pharmaceuticals from different classes here considered. For these MAC, the $M_s$ values ranged between 22 emu g$^{-1}$ and 27 emu g$^{-1}$, allowing their efficient separation from aqueous media, and the values of $S_{BET}$ ranging between 741 m$^2$ g$^{-1}$ and 795 m$^2$ g$^{-1}$ were quite satisfactory, allowing the adsorption of 61% to 70%, 69% to 77%, and 80% to 84% for AMX, CBZ, and DCF, respectively.

3.3. Morphologic and Chemical Features of the Optimal MAC

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Figure 4. SEM images of the MAC 4, MAC 7, MAC 11, and MAC 17 using a magnification of 10,000×.

The presence of magnetic iron oxides in the produced materials was evaluated by XRD, obtained results being depicted in Figure 5. The absence of peaks in the PAC highlighted the lack of a measurable crystallographic order, as this material is composed by non-graphitic and non-graphitizable carbon (Pereira et al., 2020) [15]. As for MAC 4, MAC 7, MAC 11, and MAC 17 all exhibited a characteristic XRD pattern with peaks at around 30.2°, 35.7°, 43.3°, 54.3°, 57.3°, and 62.9°, associated with the cubic spinel structure of magnetite and maghemite [15,32,43]. Although XRD results prove the existence of iron magnetic nanoparticles (magnetite and/or maghemite), they do not allow for distinguishing between these two crystalline components.

The elemental composition of PAC and the four MACs was evaluated by XRF (Table 2). The obtained data indicate that MACs are mainly composed by Fe (>95%), a value considerably higher than that of PAC (16%). These results support the successful incorporation of iron magnetic nanoparticles on the carbonaceous framework of PAC.

Evaluating their oxide composition, the results indicate the presence of Fe$_2$O$_3$ in MACs. Since these materials exhibited magnetic properties ($M_s$ ranging between 22 emu g$^{-1}$ and 27 emu g$^{-1}$) it is likely that the iron oxide nanoparticles are in the form of maghemite (γ-Fe$_2$O$_3$), and not the non-magnetic form hematite (α-Fe$_2$O$_3$). Besides that, the occurrence of maghemite instead of magnetite might result from the incomplete removal of oxygen from the reaction medium (despite of the N$_2$ flux used), contributing to the oxidation of magnetite (usually reported as being unstable in an oxidizing environment [43,44]). Other elements were also found in MACs, namely Si, Ca, S, K, Ti, Cl, and P and their presence could derive from the precursor itself and from the chemical activation (PAC production) and co-precipitation procedures, to which the precursor was subjected. Furthermore, the very low percentages found for Cl (<0.12%) and S (<0.75%), suggests the nearly total absence of unreacted iron sulphate/chloride salts in the carbon matrix (probably eliminated during the last stage of H$_2$O washing) and that the Fe content was due to the presence of
iron oxide nanoparticles in MAC’s composition. In the case of PAC, the Fe, Si, Ca, S, P, K, and Ti were detected with mass percentages varying between 4.0 and 22%, accounting for 96% of the elements detected. Just like in MACs, the presence of these elements in PAC’s composition can derive from both raw material and procedure applied to its production.

![Figure 5. XRD patterns of PAC (-), MAC 4 (-), MAC 7 (-), MAC 11 (-), and MAC 17 (-).](image)

**Table 2.** Chemical composition (expressed in mass % of each element) of PAC, MAC 4, MAC 7, MAC 11, and MAC 17, obtained by XRF analysis.

|          | Fe  | Si  | Ca   | S    | K    | Ti   | Cl    | P     | Minor Elements
|----------|-----|-----|------|------|------|------|-------|-------|-----------------|
| PAC      | 16.2| 19.1| 17.8 | 21.5 | 10.8 | 7.0  | 4.0   | 1.4   | 2.2             |
| MAC4     | 95.8| 0.98| 0.87 | 0.75 | 0.53 | 0.27 | 0.06  | 0.12  | 0.80           |
| MAC7     | 95.0| 0.91| 0.86 | 0.58 | 1.24 | 0.30 | 0.12  | 0.19  | 0.80           |
| MAC11    | 96.3| 0.80| 0.88 | 0.42 | 0.76 | 0.24 | 0.02  | 0.19  | 0.39           |
| MAC17    | 95.2| 0.61| 1.00 | 0.32 | 1.54 | 0.24 | 0.06  | 0.18  | 0.85           |

1. Minor elements detected: Al, Br, Co, Cr, Cu, Mg, Mn, Mo, Ni, Sr, V, Zn, and Zr (PAC), Al, Cr, Cu, Mg, Mn, Ni, Pd, V, Zn, Zr (MAC 4, MAC 7, MAC 11, and MAC 17).

The surface chemical composition of MAC 4, MAC 7, MAC 11, and MAC 17 was further examined by XPS and compared with that of PAC. The XPS spectra obtained for PAC, MAC 4, MAC 7, MAC 11, and MAC 17 are presented in Figure S2, as Supplementary Materials. The XPS spectrum of PAC shows two major peaks, which are the C1s and O1s, while in the case of MAC 4, besides these two, Fe2p and Fe3s peaks were also identified. Other small peaks were also visible, namely Si2p, Si2s, and N1s for all the analyzed (Figure S5).

The C1s, O1s and Fe2p peaks of MAC were deconvoluted and compared with those of PAC. Table 3 presents the component groups, binding energies and atomic concentrations of PAC and of the four MACs, while Figure 6 presents the deconvoluted C1s and O1s peaks of PAC and C1s, O1s, Fe2p peaks for MAC 4 (as for MAC 7, MAC 11 e MAC 17 the information is depicted in Figure S6, as Supplementary Materials).
Table 3. Bond assignment (and respective abundance, in %), binding energies and total atomic percentages of C1s, O1s, Fe2p, Si2p, and N1s XPS peaks of PAC, MAC 4, MAC 7, MAC 11, and MAC 17.

| Peak       | Possible Bond Assignment | PAC | MAC 4 | MAC 7 | MAC 11 | MAC 17 |
|------------|--------------------------|-----|-------|-------|--------|--------|
|            | Binding                  | (eV) | (%)   | (eV)  | (%)   | (eV)  | (%)   | (eV)  | (%)   |
| C1s        | Graphitic C              | 284.4 | 40.5 | 284.4 | 40.4 | 284.2 | 26.4 | 284.3 | 36.0 | 284.3 | 38.8  |
|            | C–C sp<sup>3</sup>; C–H  | 284.6 | 21.2 | 284.5 | 22.9 | 284.5 | 36.6 | 284.6 | 23.1 | 284.6 | 21.0  |
|            | C–O                     | 285.5 | 20.3 | 285.6 | 15.0 | 285.2 | 18.2 | 285.5 | 18.5 | 285.2 | 26.2  |
|            | C=O                     | 287.3 | 9.0  | 286.8 | 9.3  | 286.4 | 11.2 | 287.1 | 10.0 | 286.5 | 7.8   |
|            | O–C=O                   | 289.8 | 9.0  | 289.6 | 12.3 | 289.0 | 7.5  | 289.9 | 12.4 | 288.9 | 6.2   |
|            | Total carbon percentage |      | 74.9 |       | 62.6  | 57.2  |       | 60.8  |       | 58.8  |       |
| O1s        | Fe–O                    | —    | —    | 530.3 | 36.3 | 530.2 | 43.3 | 530.1 | 36.4 | 530.1 | 44.2  |
|            | C=O                     | 531.1 | 21.4 | 531.4 | 32.5 | 531.2 | 24.2 | 531.0 | 24.8 | 530.9 | 22.3  |
|            | O–H and C=O             | 532.8 | 52.2 | 532.4 | 17.6 | 532.1 | 14.5 | 531.8 | 20.1 | 531.7 | 13.9  |
|            | –C–O–C–                | 533.7 | 24.7 | 533.4 | 13.6 | 532.8 | 18.0 | 532.7 | 18.7 | 532.6 | 19.6  |
|            | Physiosorbed water      | 535.8 | 1.8  | —     | —    | —     | —    | —     | —    | —     |       |
|            | Total oxygen percentage |      | 17.8 |       | 24.4  | 28.1  |       | 25.5  |       | 26.5  |       |
| Fe2p       | Fe2p<sub>3/2</sub>, Fe–O, Fe<sup>2+</sup> | — | — | 711.1 | 20.7 | 710.8 | 21.2 | 710.9 | 21.0 | 710.7 | 19.9 |
|            | Fe2p<sub>3/2</sub>, Fe–O, Fe<sup>3+</sup> | — | — | 713.0 | 17.8 | 712.6 | 16.3 | 712.6 | 14.8 | 712.4 | 16.2 |
|            | Fe2p<sub>3/2</sub>, Fe<sup>2+</sup> satellite | — | — | 715.2 | 12.8 | 714.9 | 12.1 | 714.7 | 12.4 | 714.5 | 12.1 |
|            | Fe2p<sub>3/2</sub>, Fe<sup>3+</sup> satellite | — | — | 720.2 | 15.8 | 719.6 | 15.3 | 719.6 | 16.3 | 719.5 | 16.7 |
|            | Fe2p<sub>1/2</sub>, Fe–O, Fe<sup>2+</sup> | — | — | 724.3 | 10.4 | 724.1 | 11.9 | 724.0 | 10.8 | 724.1 | 11.3 |
|            | Fe2p<sub>1/2</sub>, Fe–O, Fe<sup>3+</sup> | — | — | 726.2 | 8.9 | 725.9 | 8.7 | 725.7 | 8.4 | 725.6 | 8.3 |
|            | Fe2p<sub>1/2</sub>, Fe<sup>2+</sup> satellite | — | — | 728.4 | 6.4 | 728.0 | 7.3 | 727.6 | 8.4 | 727.6 | 8.0 |
|            | Fe2p<sub>1/2</sub>, Fe<sup>3+</sup> satellite | — | — | 733.4 | 7.2 | 733.1 | 7.1 | 732.7 | 7.9 | 732.7 | 7.6 |
|            | Total iron percentage   |      | 0.0  |       | 6.6   | 8.7   |       | 8.4   |       | 9.5   |       |
| Si2p       | SiO<sub>2</sub>         | 103.8 | 6.3  | 102.2 | 5.0  | 102.1 | 5.3  | 101.8 | 4.8  | 101.7 | 4.7   |
| N1s        | Pyridinic N (N-6)       | 397.6 | 0.3  | 399.9 | 0.8  | 400.1 | 0.2  | 400.0 | 0.5  | 400.1 | 0.4   |
As seen in Table 3, the deconvolution of the C1s region of PAC and the four selected MACs showed the presence of 5 peaks with binding energies ranging between 284 eV and 289 eV. These binding energies were assigned to the graphitic carbon sp², the presence of C–C sp³ and C–H and other surface functional groups including C–O (ether and alcohol), C=O (carbonyl, quinones, and ketones) and O–C=O (carboxylic acids and carboxylic anhydride) [45,46]. In both PAC and MACs, the peaks with the lowest binding energies (graphitic C and C–C sp³/C–H) represent the prevailing peaks of C1s, except for MAC 7. By deconvoluting the O1s peak of PAC, a main peak at 533 eV appears and is attributed to O–H in hydroxyl groups and carbonyl (C=O) oxygen atoms in lactone and anhydrides. Besides that, two other peaks appear at 534 eV and 531 eV due to non-carbonyl oxygen atoms O–C=O in lactone and anhydrides and the carbonyl group and C=O in quinones; a small peak at 536 eV appears due to the contribution from the physisorbed water [45,46].

As for MAC materials, the deconvolution of O1s results in an additional peak at 530 eV, resulting from Fe–O [42,47]. The other peaks at 531 eV, 533 eV, and 534 eV are attributed to the oxygen in the same functional groups as in PAC and no peaks were detected at ca. 536 eV. Regarding the surface chemistry, and from the functionalities identified in O1s and C1s deconvoluted peaks (Table 3), a decrease was observed in the percentage of carbonyl, carboxyl and hydroxyl groups in the four MACs when compared with PAC. Since these surface functional groups can act as binding sites, their content may have a significant impact on the adsorption of pharmaceuticals.

The XPS peak of Fe2p shows two peaks, one corresponding to Fe2p₃/₂ peak with a binding energy between 711.4 eV and 711.8 eV and the other to Fe2p₁/₂ appearing between 724.8 and 725.2 eV. The separation between these two peaks for the four MACs varies between 13.2 and 13.8 eV and the ratio between the area of Fe2p₃/₂ and Fe2p₁/₂ peaks is ca. 2. Besides that, a satellite peak of Fe2p₃/₂ appears at around 719.6 eV and is located just about 8 eV higher than the main Fe2p₃/₂ peak. According to Yamashita and Hayes (2008), the presence of this Fe2p₃/₂ satellite peak on the XPS spectra of MAC
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materials confirms the formation of Fe$_2$O$_3$ (maghemite) nanoparticles, since this peak does not appear in the XPS spectrum of Fe$_3$O$_4$ (magnetite) [48]. The formation of Fe$_2$O$_3$ instead of Fe$_3$O$_4$ corroborates the results obtained from XRF analysis. Besides, another peak appeared at 729.5 eV corresponding to the satellite peak for Fe$_2$P$_{1/2}$. The Fe$_2$P of MAC 4 was deconvoluted, as showed in Figure 6. The Fe$_2$P$_{3/2}$ and Fe$_2$P$_{1/2}$ peaks and their corresponding satellites can be deconvoluted into Fe$^{2+}$ and Fe$^{3+}$ peaks and the lowest binding energies were always attributed to Fe$^{2+}$ (see Table 3).

The total atomic percentage of each peak, along with the elemental composition, for PAC, MAC 4, MAC 7, MAC 11, and MAC 17 is listed in Table 3. The XPS data indicate contents of 74.9% of carbon and 17.8% of oxygen for the bare PAC. As for the composite MACs, the content of carbon decreased ca. 16% to 24% after loading the carbonaceous framework with iron oxide nanoparticles, and this variation was followed by an increase in both oxygen and iron contents, corresponding to the formation of iron oxides on their surface. Only trace amounts of nitrogen (<0.8%) were detected on the surface of all materials. Besides that, the XPS spectra identified the presence of a peak at around 102 eV, corresponding to the presence of SiO$_2$ in all the five materials. The presence of silicon in these materials, with atomic concentrations varying between 4.7% and 6.3%, as stated before, might be due to the own composition of the carbonaceous precursor, namely PS, and the activation procedure applied to it.

3.4. Comparison with Waste-Based MAC in the Literature

The features of waste-based MAC 4, MAC 7, MAC 11 and MAC 17, regarding $M_s$ and $S_{BET}$, were compared with values reported in the literature (Table 4). The magnetic characteristics evidenced by the referred materials were typically superior than those obtained by other carbon materials containing magnetic iron oxide nanoparticles and applied in the adsorption of pharmaceuticals, with $M_s$ values 1.4 to 4.8 times higher [30,41,42,47,49,50]. Besides that, their $S_{BET}$ were also higher than the values reported in the literature for other MACs [30,41,42,47,49–51]. Differently, the MAC produced by Baghdadi et al. (2016) [25] presented a $S_{BET}$ value 1.6 to 1.7 times higher than that of MAC 4, MAC 7, MAC 11, and MAC 17, yet, its $M_s$ was ca. 5 times lower than for the MACs of the present work and, according to Wang et al. (2014) [40], insufficient to ensure an efficient magnetic separation ($M_s < 16$ emu g$^{-1}$). In the case of the material obtained by Rai and Singh (2018) [19], despite of the 1.4–1.6 times higher $M_s$, the $S_{BET}$ was at least 2.6 lower than the values presented by the here selected MACs.

Very few information exists in the literature regarding the application of MAC in the removal of the AMX, CBZ, and DCF from aqueous media, which highlights the need for further research concerning this issue. Published data on the adsorption of these pharmaceuticals by different MACs are shown in Table S4 (depicted as Supplementary Materials) together with results obtained in this work. As it may be observed, all the $A$ (%) in Table S4 are in the same order of magnitude, with the $A_{AMX}$, $A_{CBZ}$, and $A_{DCF}$ of the MACs produced in this work being in the range of values published in the literature [18,36,39]. However, it must be pointed out that strict comparisons between the performance of the several materials cannot be done since different experimental conditions were used in each work. This is especially evident in the case of the pharmaceutical's initial concentration and the adsorbent dose, with the lowest values being used in this study.

All the above considerations are indicative of the potential displayed by the waste-based MACs produced in this work, since they are capable of effectively adsorb AMX, CBZ and DCF from aqueous media, even when a small dose of material (35 mg L$^{-1}$) is used, and are, simultaneously, easily and quickly recovered from the treated water by applying an external magnetic field. Due to the advantages associated with these materials, in particular their effective after-use separation, they may represent a suitable and sustainable alternative to PAC (avoiding the time consuming, costly, and inefficient separation stages) in water treatment. Considering such advantages, future work is to be carried out to further evaluate the performance of the selected MACs produced in this work, namely
by determining the kinetic and equilibrium profiles towards the removal of different pharmaceuticals from WWTP effluents and exploring their regeneration/reutilization capacity by environmentally-friendly processes.

Table 4. Values of $M_s$ and $S_{BET}$ obtained for several MAC aimed at the adsorption of pharmaceuticals from water and produced by loading iron oxide nanoparticles onto different carbon precursors by different synthesis methods.

| Carbon Precursor                                  | MAC Synthesis                          | $S_{BET}$ (m$^2$ g$^{-1}$) | $M_s$ (emu g$^{-1}$) | References |
|--------------------------------------------------|----------------------------------------|-----------------------------|----------------------|------------|
| Paper mill sludge/KOH activation and pyrolysis   | Co-precipitation                       | 741–795                     | 21.6–24.9            | Present study |
| Commercial powder AC followed by HNO$_3$ treatment| Co-precipitation                       | 1241                        | 5.1                  | [25]       |
| Polyethylene terephthalate containers/pyrolysis and calcination with CO$_2$ | Co-precipitation                       | 289                         | 35.4                 | [19]       |
| Commercial powder AC followed by treatment with basic steam | Co-precipitation                       | 556                         | 5.2                  | [30]       |
| Sugarcane bagasse/NaOH activation                 | Co-precipitation                       | 43                          | 9.7                  | [47]       |
| Coconut shell/H$_2$SO$_4$ activation and pyrolysis| Co-precipitation                       | 335                         | 15.8                 | [50]       |
| Commercial PAC                                    | Oxidative hydrolysis of Fe$^{II2+}$ in alkaline media | 666–556                     | 2.3–9.8              | [41]       |
| Commercial AC                                     | Oxidative hydrolysis of Fe$^{II2+}$ in alkaline media | 535–652                     | 2.0–14.8             | [42]       |
| Commercial PAC followed by HNO$_3$ treatment      | Thermochemical methods                 | 671                         | 6.9                  | [49]       |
| Commercial granular AC                            | Ball milling                           | 486                         | 20.8                 | [51]       |

4. Conclusions

In the present work, nanocomposite materials exhibiting well-developed porous structures and containing nano-sized magnetic iron oxides in their framework were produced by a simple and cost-effective co-precipitation method and using primary paper mill sludge as PAC precursor. A FFD with mixed levels was applied and the combined effect of the synthesis conditions (Fe$^{II2+}$:Fe$^{II3+}$ salts molar ratio, PAC:Fe salts mass ratio, temperature, and pH) and their impact on both MAC’s features ($S_{BET}$ and $M_s$) and adsorptive removal of three pharmaceuticals (the antibiotic AMX, the antiepileptic CBZ and the non-steroidal anti-inflammatory DFC) was assessed. The data obtained from the multivariate analysis revealed that the mass ratio between PAC and the iron salts used in MAC’s production was the only factor significantly affecting all responses, except for the percentage of AMX adsorbed, which was not affected by any of the considered conditions. Furthermore, the obtained PCA score graph showed the definition of five distinct clusters and highlighted an opposite correlation between $S_{BET}$ and $M_s$ and a strong correlation between $A_{CBZ}$, $A_{DCF}$, and $S_{BET}$ responses. As for the adsorption of AMX, no correlation with the other responses was observed. Finally, a 3D graphical analysis of $S_{BET}$, $M_s$ and $A_{pooled}$ responses allowed for the selection of the production conditions used for MAC 4, MAC 7, MAC 11, and MAC 17 as the most favourable, with these materials exhibiting high $S_{BET}$, large adsorption percentages (at relatively low MAC doses) ranging between 61–70%, 69–77%, and 80–84% for AMX, CBZ, and DCF, respectively, and still guaranteeing an efficient after-use recovery by magnetic separation ($M_s$ between 22 emu g$^{-1}$ and 27 emu g$^{-1}$).

Supplementary Materials: The following are available online at https://www.mdpi.com/2079-4991/11/2/287/s1, Table S1: Physical and chemical properties of amoxicillin tri-hydrate (AMX), carbamazepine (CBZ) and sodium diclofenac (DCF), Table S2: Values obtained for the specific surface
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