

Article

Ozone Kinetic Studies Assessment for the PPCPs Abatement: Mixtures Relevance

João Gomes ^{1,*} , Carla Bernardo ¹, Fátima Jesus ² , Joana Luísa Pereira ³  and Rui C. Martins ¹ 

¹ CIEPQPF—Chemical Engineering Processes and Forest Products Research Center, Department of Chemical Engineering, Faculty of Sciences and Technology, University of Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal; carla_1997@live.com.pt (C.B.); martins@eq.uc.pt (R.C.M.)

² CESAM—Centre for Environmental and Marine Studies, Department of Environment and Planning, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal; fatima.jesus@ua.pt

³ CESAM—Centre for Environmental and Marine Studies, Department of Biology, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal; jpereira@ua.pt

* Correspondence: jgomes@eq.uc.pt; Tel.: +351-239-798-723

Abstract: The increasing consumption of pharmaceutical and personal care products (PPCPs) by humankind has been causing an accumulation of contaminants (commonly referred to as contaminants of emerging concern), in effluents and water resources. Ozonation can be used to improve the removal of these contaminants during water treatment to alleviate this burden. In this work, the degradation of methyl (MP), propylparaben (PP), paracetamol (PCT), sulfamethoxazole (SMX), and carbamazepine (CBZ) by ozonation was assessed both for individual compounds and for mixtures with increasing complexity (two to five compounds). Ozonation was performed at pH3 to gain an insight on the exclusive action of molecular ozone as oxidizing agent. The degradation of contaminants was described as a function of time and transferred ozone dose, and the corresponding pseudo-first order kinetic rate constants (k') were determined. PPCPs were degraded individually within 1.5 to 10 min. CBZ was the most quickly degraded ($k' = 1.25 \text{ min}^{-1}$) and MP the most resistant to ozone ($k' = 0.25 \text{ min}^{-1}$). When in the mixture, the degradation rate of the contaminants was slower. For parabens, the increase of the number of compounds in the mixture led to an exponential decrease of the k' values. Moreover, the presence of more PPCPs within the mixture increased energy consumption associated with the treatment, thereby reflecting higher economic costs.

Keywords: ozonation; kinetics studies; contaminants of emerging concern; energy consumption; by-products



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1. Introduction

Drinking water is one of the most important resources for the humankind [1]. Currently, drinking water scarcity is a major concern, as it affects both public health and the economy [2]. The exponential population growth, increased industry development, and consequent effects concerning climate change have been leading to an increased water demand across the planet [1]. It is expected that the demand for affordable and reliable water to support economic development will grow to about 40% by 2030 [3]. In a more favorable scenario, but nonetheless still concerning one, Boretti and Rosa [4] reported that global water demand is expected to have an increase of up to 20–30% by 2050. Therefore, wastewater reclamation is important issue to face and the impact of water scarcity must be minimized. Within this perspective, wastewater treatment plants (WWTP) need to improve their effectiveness regarding the removal of contaminants of emerging concern (CECs), such as the pharmaceutical and personal care products (PPCP), with the addition of efficient tertiary processes [2,5].

Every day, industries, agriculture, and even the general population use water and then release numerous compounds into wastewater. These pollutants enter the water cycle and

have a high impact on human and environmental health. In recent decades, the presence of CEC has been reported in wastewater in concentrations that can range from a few ng L^{-1} to a few hundred $\mu\text{g L}^{-1}$ [6]. This can be related to the improper disposal of unused PPCP and also to the fact that drug residues are excreted by humans and animals through urine and feces [7]. The most common PPCPs found in water resources due to their recurrent societal use are antimicrobial agents, antibiotics, and pain killers [8]. Among antimicrobial agents, there are parabens, such as methyl- (MP), ethyl- (EP) and propylparaben (PP). These are often used as antimicrobial and preservative agents in cosmetics, pharmaceuticals as well as in food and beverage processing [9]. The antimicrobial properties of parabens improve with increasing alkyl chain lengths [9].

Some drugs such as diclofenac, carbamazepine, and diazepam are not easily removed by conventional wastewater treatment [10]. Carbamazepine (CBZ) is a widely used anticonvulsant; only about 28% of CBZ consumed is metabolized by the human body and the rest is readily excreted. Therefore, this is one of the most common compounds in different water matrices [11]. Paracetamol (PCT, also known as acetaminophen) is one of the most popular pain killers worldwide and has a low level of removal in WWTP [12]. It is frequently detected in sewage treatment plant effluents, surface water, and drinking water, which links to the fact that around 58–68% of the unchanged compound is excreted by the human body [13]. Within PPCPs, there is one group of special relevance, namely the antibiotics group. Sulfamethoxazole (SMX) is one of the most common antibiotics found in effluents [14]. The conventional biological treatments are not efficient in removing this drug since it is not adsorbed or biodegraded by active sludge, owing to its polarity and antibacterial nature [14]. MP, PP, SMX, PCT, and CBZ were selected for the present study, representing a wide variety of classes of PPCPs and thus aiming to be representative of the diversity of chemicals currently found in wastewaters.

WWTPs are the main entry route for these compounds into the environment, and it is thus necessary to develop efficient technologies for their removal from treatment matrices. Advanced oxidation processes (AOPs) have been pointed out as promising methods for wastewater treatment due to their high mineralization capacity, quick oxidation reaction rate, and the interaction with a wide range of CECs [15]. AOPs are characterized by the production of radicals, namely the highly reactive hydroxyl radical, which are able to oxidize and decompose several recalcitrant species into molecules potentially less harmful to the environment (or ideally promote their complete mineralization) [16]. Ozonation stands out among these processes due to the high oxidizing potential of molecular ozone (2.07 V), allowing an efficient removal of contaminants from water. However, one of the drawbacks of ozone is its selective character; it mainly attacks functional groups rich in electrons such as double bonds, amines, and activated aromatic rings [17]. In the case of hydroxyl radicals, their oxidizing potential is higher (2.80 V), having a non-selective character reflecting in the likely degradation of a wide range of micropollutants present in the wastewater sources. The oxidizing power of ozone is highly dependent of the medium pH. Its action with contaminants can follow a direct pathway ($\text{pH} < 5$) resulting from the reaction between ozone and the micropollutant [18,19].

The use of ozone has several advantages, such as an easy production from air or oxygen and fast reactions. Also, when in excess in water, ozone decomposes into oxygen without creating residues [20]. The ozonation process allows high water recovery rates without the production of wastes or sludges and has the additional advantage of being a process that is easy to adapt to fluctuations in the characteristics and conditions of the incoming effluent [10]. In some countries, this process is already implemented at large scale [21], well accommodating improvements. Despite this, ozonation has some disadvantages as it can lead to the production of refractory by-products and considering that ozone is an explosive, toxic gas with a high energy demanding production. In this way, the systematic study of PPCPs degradation kinetics under ozonation is critical before up-scaling since it provides meaningful information for optimizing several operational variables (e.g., reactor size, process conditions, and for minimizing operating costs) [22]. Varying experimental

conditions such as temperature, contaminant concentrations, transferred ozone dose (TOD) value and pH allow a deeper understanding of the operating parameters that are most favorable to an effective and efficient contaminant degradation.

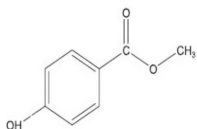
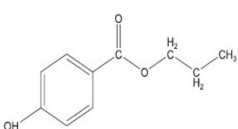
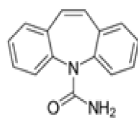
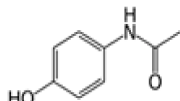
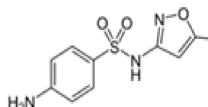
The present work aimed to analyze the effect of molecular ozone (isolated by performing the reactions at pH 3) in the oxidation of different PPCPs, namely MP, PP, PCT, SMX, and CBZ, either individually or as mixtures of increasing complexity. To our knowledge, this is the first study analyzing the impacts of the addition of different contaminants with different susceptibility for reacting with ozone in ozone consumption (and energy cost), as well as over the pseudo-first order kinetic constants of degradation. The apparent kinetic constants for the different compounds were determined based on reaction time as well as on the transferred ozone dose (TOD) values. Moreover, by-products of the ozonation of MP, PP, and SMX were identified. This work also presents an economic assessment based on the TOD value obtained for mixtures, improving on the relevance of the data for the process scale-up and reactor design.

2. Materials and Methods

2.1. Chemicals

The pharmaceuticals and personal care products (PPCP) used in this work (methylparaben (MP), propylparaben (PP), carbamazepine (CBZ), paracetamol (PCT) and sulfamethoxazole (SMX)) were acquired from Sigma-Aldrich (Saint Louis, MO, USA) (99% of purity). Their molecular structure and specific characteristics such as pKa and Kow are presented in Table 1 [PubChem].

Table 1. Elemental characteristics of PPCPs used in this work.

Chemical Structure					
Name	Methylparaben	Propylparaben	Carbamazepine	Paracetamol	Sulfamethoxazole
Molecular Formula	C ₈ H ₈ O ₃	C ₁₀ H ₁₂ O ₃	C ₁₅ H ₁₂ N ₂ O	C ₈ H ₉ NO ₂	C ₁₀ H ₁₁ N ₃ O ₃ S
Molecular Weight	152.15 g mol ⁻¹	180.20 g mol ⁻¹	236.27 g mol ⁻¹	151.16 g mol ⁻¹	253.28 g mol ⁻¹
Water Solubility (at 25 °C)	25 mg mL ⁻¹	0.50 mg mL ⁻¹	0.018 mg mL ⁻¹	14 mg mL ⁻¹	0.50 mg mL ⁻¹
pKa	8.50	8.50	13.9	9.38	1.6 and 5.7
Log Kow	1.96	3.04	2.45	0.46	0.89

2.2. Experimental Set-Up

Synthetic effluent solutions were prepared dissolving each PPCP in ultrapure water. All PPCPs were dosed at a concentration of 1 mg L⁻¹ regardless of the experimental stage. This concentration was selected in order to reach detectable concentrations of by-products formed during the reaction and was selected in accordance with other literature studies [11,12,14]. Their degradation through the ozone action was first analyzed for each parent compound individually. Then, to assess the effect of the number of contaminants on the ozone performance towards their abatement, the degradation of each PPCP through ozonation was analyzed for mixtures with 2, 3, 4, or 5 contaminants dissolved in ultrapure water. The composition of each mixture is described in Table 2.

Table 2. Composition of PPCPs mixtures used in the ozone reactions (each compound dosed at 1 mg L⁻¹).

	Mix.2	Mix.3	Mix.4	Mix.5
Composition	MP + PP	MP + PP + PCT	MP + PP + PCT + SMX	MP + PP + PCT + SMX + CBZ

MP, methylparaben; PP, propylparaben; PCT, paracetamol; SMX, sulfamethoxazole; CBZ, carbamazepine.

Prior to the onset of the ozonation reaction, the samples pH was corrected to 3 (using a HCl solution) to prevent the production of hydroxyl radicals from ozone decomposition.

Ozonation was performed in a 2-L glass reactor with a thermostatic water bath to keep a constant temperature (25 ± 1 °C) (Figure 1). The solution was continuously stirred by a magnet at 700 rpm. The duration of each ozonation reaction depended on the contaminant/mixture used, and during the reaction the samples were taken for different withdrawn intervals time. The experiments were performed in duplicate and the standard error between replicates was always below than 5%.

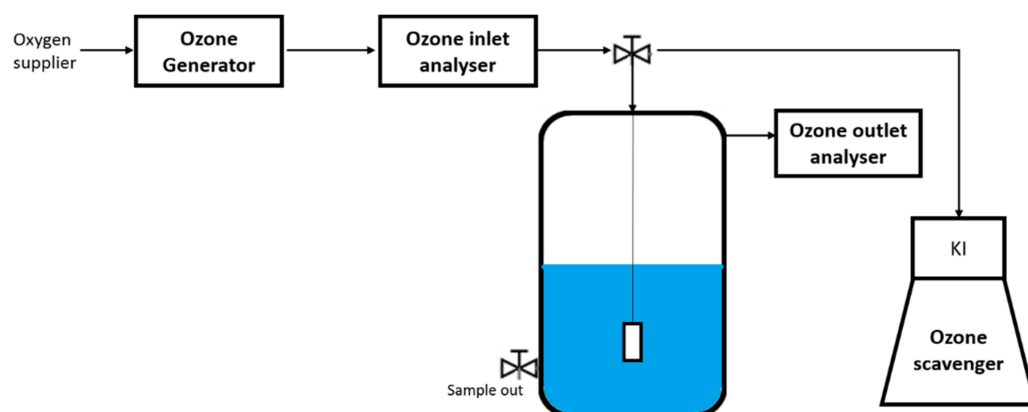


Figure 1. Ozonation scheme used in the experiments.

Ozone was produced from pure oxygen (99.9%) using an ozone generator (802N, BMT). The inlet ($[O_3]^{in}$) and outlet ($[O_3]^{out}$) concentrations, in $mg\ L^{-1}$, were measured by ozone gas analyzers (BMT 963 vent and BTM 964 vent, respectively). Based on the values measured by the ozone meters it is possible to determine the transferred ozone dose (TOD), in $mgO_3\ L^{-1}$, following Equation (1), where V_{liquid} represents the volume of effluent to be treated (1 L) and Q_{Gas} represents the inlet gas flow rate ($0.2\ L\ min^{-1}$). The numerical integration through trapezoidal rule was made for Equation (1) to obtain the TOD values during the reactions due to the values of inlet and outlet gas concentration for different periods of time with the same gas flow.

$$TOD = \int_0^t \frac{Q_{Gas}}{V_{liquid}} \times ([O_3]^{in} - [O_3]^{out}) \times dt \quad (1)$$

After leaving the reactor, the outlet gas stream passes through a potassium iodide (KI) solution to trap the residual ozone at the gas phase before being released to the atmosphere.

2.3. Analytical Methods

High-performance liquid chromatography (HPLC) (Beckman Coulter System Gold, Brea, CA, USA) was used to analyze the samples collected throughout the reactions, for detection and quantification of parent contaminants and some of the generated by-products. The mobile phase ($0.5\ mL\ min^{-1}$) consisted of a mixture of 50:50 methanol: acidic water (0.1% orthophosphoric acid), following through a C18 column (SiliaChrom) at 40 °C. The sample injection volume was 100 μ L. The identification of parabens, CBZ and PCT was performed at $\lambda = 255\ nm$, whereas SMX was identified at $\lambda = 280\ nm$.

3. Results and Discussion

3.1. Degradation of Individual PPCPs

Firstly, to assess the preference of ozone towards each contaminant, the degradation profile of each PPCP alone was addressed. The samples taken during the treatment were analyzed by HPLC which allows evaluating the contaminants concentrations evolution. The pseudo-first order kinetic rate constants for the degradation of each contaminant were

calculated, both as a function of time and TOD. The ozone action on each contaminant, individually, is depicted in Figure 2.

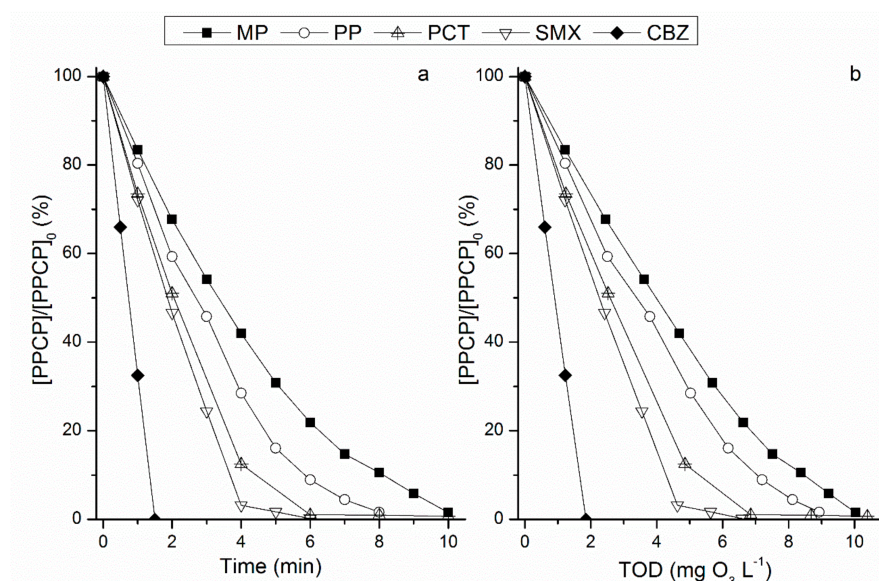


Figure 2. Normalized concentration of methylparaben (MP), propylparaben (PP), paracetamol (PCT), sulfamethoxazole (SMX), and carbamazepine (CBZ) during ozonation as function of time (a) and TOD (b).

The tested PPCPs were very susceptible to the ozone action since 10 min were enough to achieve the total removal of the initial contaminants. Moreover, the maximum TOD value registered was of $10 \text{ mg O}_3 \text{ L}^{-1}$ required to complete MP degradation. The degradation of the different PPCPs as a function of both time and TOD present analogous patterns, except that the similarity of MP and PP degradation curves was higher when TOD was considered. The most susceptible PPCP to the ozone action was CBZ. In fact, the tricyclic aromatic rings structure of CBZ (Table 1) makes this species highly electrophilic which promotes the action of molecular ozone [23]. On the other hand, parabens were the contaminants with lower degradation rates considering that, at acidic pH, the route of degradation is only through molecular ozone reactions [20]. Doná et al. [24] proved that the pH of the initial mixture is the most significant factor for the degradation of parabens by ozone, obtaining the best results at alkaline pH. Consistently, Tay et al. [22] verified that the ozonation of a mixture of five parabens (MP and PP included) under acidic pH follows a pseudo-first order kinetic rate constant about two-fold lower than at neutral pH. On the contrary, ozone has a strong effect on the removal of SMX. This is due to the electron donating amino group and the aromatic ring (Table 1) that are susceptible to molecular ozone attack [25]. In agreement, Chen and Wang [26] concluded that, at $\text{pH} = 5.2$, ozone was able to fully remove about 20 mg L^{-1} of SMX in 12 min. These authors analyzed the effect of the hydroxyl radical scavenger in addition and the degradation outcome was similar, which confirms the affinity of molecular ozone with aromatic and double bonds [18,23,26].

From the degradation profiles of single contaminants (Figure 2), an initial stage where the degradation is more accentuated is clearly identifiable, and this stage was considered for the determination of the rate constants [22]. The degradation of PPCPs can be approximated to a pseudo-first order kinetic model, where the rate of reaction for ozone (note that at $\text{pH} 3$, only molecular ozone should be considered) can be obtained from the two-film theory in a gas-liquid process [27]. After some simplifications proposed by different authors, such as that considering the low solubility of ozone in water [22,28], the pseudo-first order kinetic

model can be described as a function of time or as a function of TOD (Equations (2) and (3), respectively, adapted from [22,29]).

$$C/C_0 = e^{-k'_{\text{obs}} t} \quad (2)$$

$$C/C_0 = e^{-k'_{\text{obs}} \text{TOD}} \quad (3)$$

In Equations (2) and (3), C_0 and C represent the PPCP concentration before the ozonation reaction (time zero) and during reaction at a given time point t (min), respectively; k'_{obs} is the pseudo-first order kinetic rate constant (where a is the number of contaminants in the treated solution (in this case 1) which was determined from the degradation profile in terms of time ($k'_{\text{obs}}t$) and in terms of TOD ($k'_{\text{obs}}\text{TOD}$). The pseudo-first order kinetic rate constants calculated from our results in terms of time and in terms of TOD values are presented in Table 3.

Table 3. Pseudo-first order kinetic rate constants of ozone-treated contaminants as a function of time (k'_1) and as a function of TOD ($k'_{1,\text{TOD}}$), with the corresponding adjusted coefficients of determination (adj R^2).

	MP	PP	PCT	SMX	CBZ
k'_1 (min^{-1}) (adj R^2)	0.25 (0.98)	0.33 (0.97)	0.42 (0.97)	0.50 (0.95)	1.25 (0.90)
$k'_{1,\text{TOD}}$ (mgO_3^{-1}) (adj R^2)	0.23 (0.96)	0.27 (0.96)	0.35 (0.96)	0.42 (0.94)	1.02 (0.90)

The pseudo-first order kinetic rate constant values were similar when expressed based on time or TOD, which means that the time required to achieve the complete degradation of PPCPs is related with the transferred ozone dose for the reaction media. For the selected PPCPs this is allowed since their molecular structure have aromatic rings that favor the molecular ozone action [18]. The same conclusions can be taken when analyzing the degradation profiles depicted in Figure 2. CBZ presents the highest degradation kinetic constant value and MP presents the lowest. The kinetic rate constants for MP and PP are similar since their molecular structure is analogous; the value for PP was slightly higher due to the extended alkyl chain [30]. The kinetic rate constants were also similar between PCT and SMX, both slightly higher compared to parabens, which can relate to the presence of amine and amino groups with higher electrophilic character [25,26].

A previous study reported a pseudo-first order kinetic rate constant of 0.087 min^{-1} by ozonation, for an initial PCT concentration of 100 mg L^{-1} , at pH 6.8 and an ozone flow rate of 5 L min^{-1} [31]. This constant is about five-fold lower than that of the present study (see Table 3), which is likely related to the higher initial concentration used in referred study. Indeed, the higher concentration of parent compounds can lead to the production of higher concentrations of by-products during the reaction that will compete for ozone, which can decrease significantly the kinetic rate [22]. For SMX, Liu et al. [32] reported a pseudo-first order kinetic rate constant of 0.366 min^{-1} for an initial concentration of 1 mg L^{-1} , at pH 7 and an ozone dose of $2.1 \text{ mg O}_3 \text{ L}^{-1}$. This value is slightly lower than the one obtained in the present study (see Table 3), which can reflect the lower dose of ozone comparing to the TOD used herein ($6 \text{ mg O}_3 \text{ L}^{-1}$). This also seems to support that the ozone dose is more relevant than pH for SMX abatement rates. Regarding CBZ, Giri et al. [33] reported a pseudo-first order kinetic rate constant by ozonation of about 1.07 min^{-1} , using an ozone concentration of 2 mg L^{-1} and an initial pH of the mixture of 4.7. In general, the pseudo-first order kinetic rate constants reported in the literature are similar to those obtained for the present study at pH 3, which clearly indicate that for individual compounds ozone is the main responsible for the oxidation of molecules with high electronic density composed by amine groups, aromatic ring and double bonds [18,26,33].

Tay et al. [22] studied the ozonation of MP and PP at pH 6.9 and an ozone dose of 0.67 g h^{-1} , and obtained two distinct kinetic stages during the reaction. The pseudo-first

order kinetic rate constant observed in the first stage was smaller than that observed in the second stage. For MP, the apparent kinetic constants of 0.21 and 0.36 min^{-1} were calculated for the first and second stage, while in the case of PP, the values were of 0.20 and 0.40 min^{-1} , respectively. These kinetic rate constants were obtained for the mixture of five parabens (see the discussion dedicated to mixtures in further sections), and besides this aspect, their results can be comparable with ours (Table 3).

By-Products Assessment

Due to the low mineralization capacity of ozone, the degradation of initial compounds such as those considered in the present study will produce refractory compounds difficult to remove [18,34]. In the case of reactions that use MP and PP, by-products such as 4-hydroxybenzoic acid (4-HBA), 3,4-dihydroxybenzoic acid (3,4-DHBA), 2,4-dihydroxybenzoic acid (2,4-DHBA), and 3,4-dimethoxybenzoic acid (3,4-DMBA), were identified. According to previous studies, the main by-products obtained from parabens ozonation are 4-HBA, hydroquinone (HQ), and 1,4-benzoquinone (BZQ) [22,29], but HQ and BZQ were not identified herein, which should relate to the relatively low initial concentration of parabens. For SMX, by-products such as BZQ and 3-Amino-5-methylisoxazole (AMI) are frequently detected [35]. In the present study, it was only possible to detect AMI since the SMX peak retention time is coincident with the BZQ peak in the applied HPLC method. The presence of by-products was verified during the reaction of CBZ with ozone, but their identification was not accomplished. Typically, by-products such as 1-(2-benzaldehyde)-(1H,3H)-quinazoline-2,4-dione (BQD), 1-(2-benzaldehyde)-4-hydro-(1H,3H)-quinazolin-2-one (BQM) and 2,2'-azanediylidibenzaldehyde (TP225), can be obtained by ozonation of CBZ [23]. According to Kråkström et al. [23], 74% of CBZ is converted to BQM and only 4% on TP225 after 240 min of ozonation. Consistently, a by-product peak was increasingly detected along CBZ degradation through ozone that likely relates to BQM formation. Figure 3 presents the by-products identified and quantified through the MP, PP and SMX ozone reaction. The main by-products of these parent compounds were quantified, and the areas were normalized by the maximum area of each by-product.

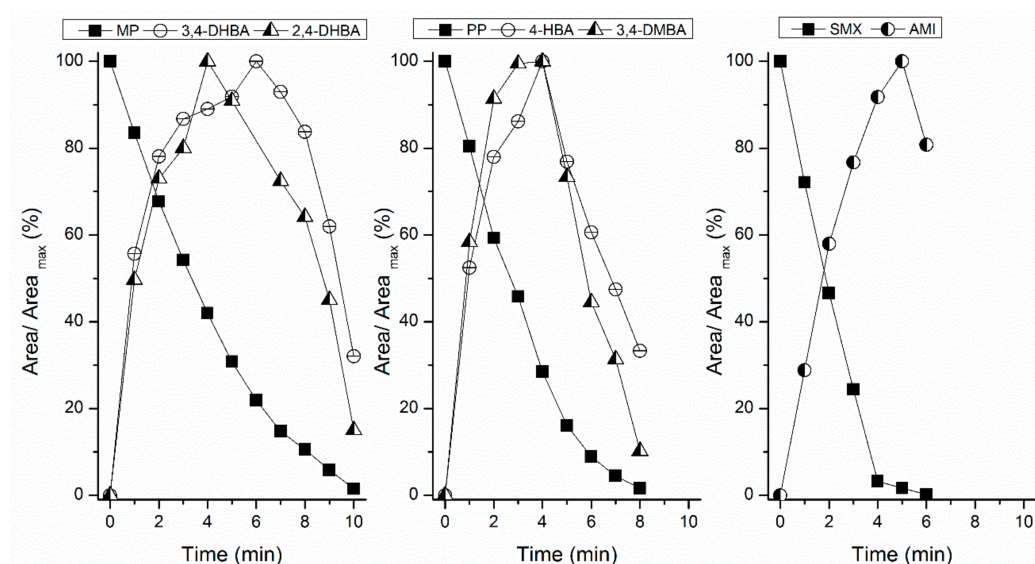


Figure 3. Normalized areas of MP, PP, and SMX and respective by-products obtained during ozonation.

MP degradation promotes the production of 2,4-DHBA and 3,4-DHBA as main by-products, with the area maxima at 4 and 6 min, respectively (Figure 3). At the end of the reaction, these compounds persist in the solution while MP was almost completely removed. During PP degradation 4-HBA and 3,4-DMBA were quantified, the latter presenting a lower area value compared to 4-HBA. In this case, both by-products achieve their maximum

value at the same time (6 min), remarkably decreasing afterwards. At the end of reaction, the amount of 4-HBA is higher compared with 3,4-DMBA (Figure 3). Although 4-HBA is one of the most common by-products obtained in ozonation processes [22], it was not identified through MP degradation. The propyl group is more electrophilic than the methyl group, which enhances the ozone action to break this alkyl bond producing 4-HBA, hence favoring the dealkylation instead of hydroxylation. During MP degradation, ozone should favor the hydroxylation of aromatic rings attack, leading to the production of 2,4-DHBA and 3,4-DHBA. Despite the similar molecular structure of MP and PP (Table 1), it is clear that the ozone attack pathway towards the target parent compounds was different, since the main by-products obtained were different. The degradation of SMX, which is a very susceptible molecule to be attacked by ozone, resulted in the accumulation of AMI as the main by-product. In fact, during the ozone reaction, AMI appears early, and its concentration increases before SMX becomes practically degraded. Then, at the end of the reaction, when achieving the complete removal of SMX, the AMI amount in the solution is higher, compared to what was found for other by-products resulting from MP and PP individual degradation.

3.2. Degradation of PPCPs in Mixture

The previous section revealed that ozone is a powerful oxidant for the selected PPCPs, and presents also some selectivity for some of the organic molecules. For example, CBZ and SMX are very susceptible to ozone attack when tested individually. However, in the wastewater treatment plants these micropollutants typically occur in complex matrices of different classes of contaminants and along other organic and inorganic compounds that can reduce the ozone efficiency [18,19,34].

Therefore, the effect of ozone action (acidic pH) over the PPCPs was also evaluated for mixtures of contaminants, and the obtained degradation profiles are shown in Figure 4.

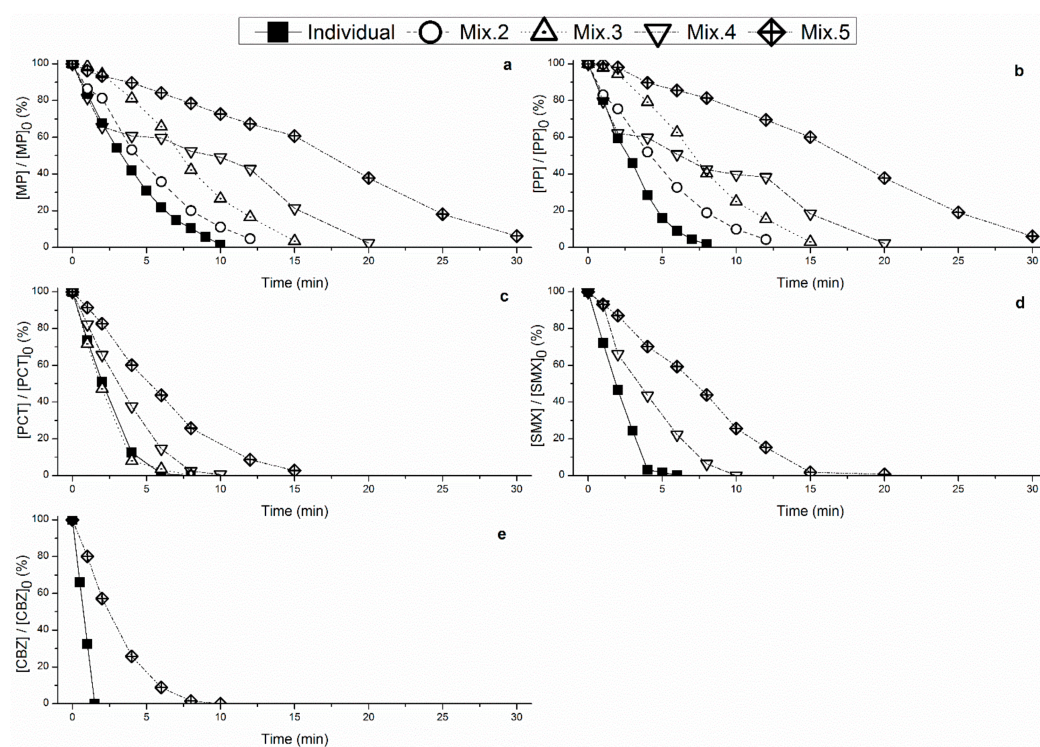


Figure 4. Normalized concentration of MP (a), PP (b), PCT (c), SMX (d), CBZ (e), during ozonation for the case where individual PPCPs were applied and for different mixtures.

The number of contaminants has a pronounced impact on the degradation profile of the parent compounds. The slope of the degradation curve for the different micropollutants

decreases with the addition of the PPCPs to mixture, reflecting slower degradation rates (Figure 4). When focusing on MP and PP (Figure 4a,b), this effect was particularly pronounced, and the degradation curves of those compounds for Mix.4 and Mix.5 are almost linear due to the addition to the mixture of molecules more favorable to ozone attack, such as CBZ and SMX [23,25,26]. PCT in the Mix.3 (joined to MP and PP) had a degradation profile slightly better than when it was degraded individually, which can be proven by the respective k'_3 (Table 4). Despite the presence of MP and PP, the degradation of PCT did not suffer any delay, which highlights the ozone selective character, mainly attacking functional groups such as double bonds, amines and activated aromatic rings [17,25]. In fact, parent mixtures of increasing complexity can promote antagonistic or synergistic effects over the PPCPs degradation [36,37]. In the case of Mix.2 the presence of two parabens promotes an antagonistic effect on their degradation, since more time and TOD were needed to achieve their removal. The degradation of Mix.3 follows the second order kinetic rates for ozone at pH 2, with values of $3.3 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$, $3.9 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$ and $2.5 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ for MP, PP and PCT, respectively [10,38,39]. The presence of parabens shows the synergistic effect over PCT degradation, since its degradation was faster when in the Mix.3 compared to when it was studied alone. Naddeo et al. [36] verified an antagonistic effect in ozonation of diclofenac, SMX and CBZ when the mixture was used, since the individual degradation for single solutions was lower than that in mixtures. However, when another ozone attractive species was introduced (i.e., SMX or CBZ in Mix.4 and Mix.5, respectively), the pseudo-first order kinetic rate for PCT and for the other contaminants referred decreased. In the case of Mix.4 and Mix.5 the antagonistic effect was observed over the all of PPCPs degradation since the degradation rate was lower compared to the individual case.

Table 4. Pseudo-first order kinetic rate constant of ozone-treated contaminants, in mixture as function of time. (k'_1) refers to the PPCP individually, whereas k'_2 , k'_3 , k'_4 , and k'_5 , refer to Mix.2, Mix.3, Mix.4 and Mix. 5, respectively. The corresponding adjusted coefficients of determination ($\text{adj } R^2$) are also presented.

	MP	PP	PCT	SMX	CBZ
k'_1 (min^{-1}) ($\text{adj } R^2$)	0.252 (0.98)	0.331 (0.97)	0.425 (0.98)	0.496 (0.95)	1.255 (0.90)
k'_2 (min^{-1}) ($\text{adj } R^2$)	0.188 (0.98)	0.196 (0.98)			
k'_3 (min^{-1}) ($\text{adj } R^2$)	0.123 (0.92)	0.127 (0.93)	0.453 (0.96)		
k'_4 (min^{-1}) ($\text{adj } R^2$)	0.083 (0.90)	0.098 (0.92)	0.288 (0.98)	0.255 (0.96)	
k'_5 (min^{-1}) ($\text{adj } R^2$)	0.049 (0.90)	0.051 (0.92)	0.178 (0.96)	0.131 (0.96)	0.342 (0.98)

The increment of the number of PPCPs in the mixture increased the time required for the total removal of the initial contaminants (Figure 4a–d). For example, the time required for the complete degradation of MP for Mix.2, Mix.3, Mix.4, and Mix.5, was 12, 15, 20, and 30 min, respectively. This steady increase in removal time ranges should relate to the fact that a more complex initial mixture will lead to the formation of more by-products that will compete by ozone and will reduce the ozone efficiency towards the parent compounds.

The pseudo-first order kinetic rate decreases with the increase in the complexity of the mixture, except for the PCT in the case of Mix.3 (Table 4).

As evident from Table 4 the adjusted R^2 decreases when the number of micropollutants in the initial mixture increases for the molecules less reactive with ozone (MP and PP). This suggests that, for these molecules and under the specific setup conditions, the pseudo-first order kinetic model does not fit so well. On the other hand, for the molecules more susceptible towards ozone attack, the pseudo-first order kinetic model proves to be a good approach even when ozonation is applied to complex mixtures.

The results obtained show a decrease of k' with mixture complexity. Thus, higher residence times will be required in the ozone reactor to achieve total PPCPs removal when the contaminants' mixture is more complex. For the ozonation of a mixture of five parabens, Tay et al. [22] verified that the increase in the contaminants' initial concentration from 0.5 to 1 M led to the exponential decrease of the respective pseudo-first order kinetic rate constants. For comparative purposes, the pseudo-first order kinetic constants for MP and PP obtained herein were plotted as a function of the number of PPCPs present in the initial mixture (Figure 5).

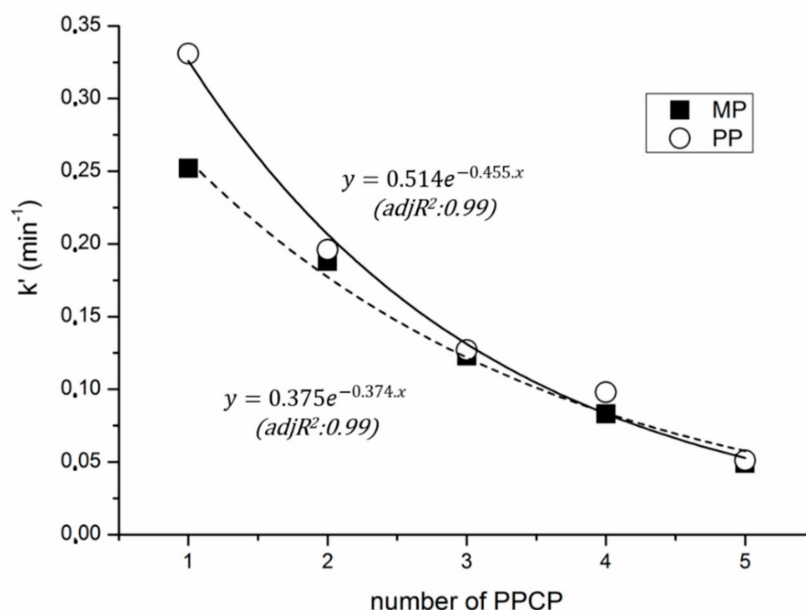


Figure 5. Variation of pseudo-first order kinetic constant rate for MP and PP with the number of contaminants present in the initial mixture.

MP and PP kinetic rate constants decrease exponentially with the number of contaminants in the mixture (Figure 5). For MP, the most recalcitrant micropollutant to ozone action among those tested, the fitted exponential equation parameters present lower values comparing to PP. Moreover, if one disregards the first point (micropollutants degraded individually), the curves are similar. The equations obtained through this fitting exercise may be an interesting approach to estimate the pseudo-first order kinetic rate constants for MP and PP degradation by ozonation when more PPCPs composed by molecular structures containing aromatic rings or double bonds are added to a mixture. For the other PPCP investigated in this work, it was not possible to estimate these parameters since too few points were available.

The degradation profiles as function of TOD for different PPCPs were very similar (data not shown as per curve slope similarity). Comparing the kinetic constants as a function of time (Table 4) with the kinetic rate constants as a function of TOD (Table 5), it is clear that the pseudo-first order kinetic rate constant remains similar either for the time or for the TOD. This suggests that the time required to achieve the complete degradation of PPCPs in mixture is related with the TOD value of the reaction, similarly to what was observed regarding individual PPCPs degradation.

3.3. General Economic Considerations

Ozone application for contaminants removal can have substantial operating costs that can be minimized with the usage of low ozone doses [30,40]. The concentration of micropollutants in the water sources can be found within the ng L^{-1} or $\mu\text{g L}^{-1}$ range [6,10]. In this way, the costs to treat micropollutants can be estimated based on the TOD values. In fact, for real scale applications and bearing in mind the economic feasibility of the

process, TOD will be more relevant since it considers the ozone dose ($\text{mgO}_3 \text{ L}^{-1}$) that is consumed during the process. In fact, ozone production is the main operating cost of this technology and must be considered while optimizing the process. To determine the energy consumption for the degradation of individual PPCPs and tested mixtures, the reference value of energy to produce ozone from an oxygen stream was set at $12 \text{ kWh kgO}_3^{-1}$ [41]. Table 6 presents the energy consumption required to achieve the total removal of different PPCPs individually or in mixture.

Table 5. Pseudo-first order kinetic rate constant of ozone-treated contaminants, in mixture as function of TOD values. $k'_{1 \text{ TOD}}$ refers to the PPCP individually, whereas $k'_{2 \text{ TOD}}$, $k'_{3 \text{ TOD}}$, $k'_{4 \text{ TOD}}$, and $k'_{5 \text{ TOD}}$, refer to Mix.2, Mix.3, Mix.4, and Mix.5, respectively. The corresponding adjusted coefficients of determination (adj R^2) are also presented.

	MP	PP	PCT	SMX	CBZ
$k'_{1 \text{ TOD}} (\text{mgO}_3^{-1})$ (adj R^2)	0.228 (0.96)	0.271 (0.96)	0.352 (0.96)	0.422 (0.94)	1.022 (0.90)
$k'_{2 \text{ TOD}} (\text{mgO}_3^{-1})$ (adj R^2)	0.171 (0.98)	0.178 (0.96)			
$k'_{3 \text{ TOD}} (\text{mgO}_3^{-1})$ (adj R^2)	0.119 (0.92)	0.123 (0.90)	0.393 (0.97)		
$k'_{4 \text{ TOD}} (\text{mgO}_3^{-1})$ (adj R^2)	0.083 (0.90)	0.097 (0.92)	0.248 (0.98)	0.211 (0.95)	
$k'_{5 \text{ TOD}} (\text{mgO}_3^{-1})$ (adj R^2)	0.057 (0.88)	0.059 (0.86)	0.167 (0.93)	0.129 (0.91)	0.294 (0.97)

Table 6. Energy consumption for PPCPs removal individually or in mixture through ozone oxidation.

Energy Consumption (kWh m^{-3})	Individual	Mix.2	Mix.3	Mix.4	Mix.5
MP	0.120	0.137	0.174	0.221	0.264
PP	0.107	0.137	0.174	0.221	0.264
PCT	0.104		0.100	0.146	0.166
SMX	0.080			0.126	0.201
CBZ	0.022				0.123

High electronic density species such as CBZ require lower energy consumption for total removal, whereas MP degradation implies a higher energy consumption (Table 6). Moreover, as expected, the energy consumption increases with the increasing complexity of PPCPs mixture, due to the higher ozone doses needed to achieve the complete removal of such micropollutants. In order to treat a mixture of micropollutants present in secondary wastewater with an average ozone dose of $3.2 \text{ mgO}_3 \text{ L}^{-1}$, Hollender et al. [41] determined an energy consumption of 0.035 kWh m^{-3} . Margot et al. [42] analyzed the removal of about 70 CECs from a secondary effluent in pilot plant an ozonation and sand-filtration system, showing that the removal of up 80% of micropollutants required about 0.117 kWh m^{-3} of energy consumption with a dose of $5.7 \text{ mgO}_3 \text{ L}^{-1}$. These benchmarks are in accordance with the present study since the initial CECs concentration was within the $\mu\text{g L}^{-1}$ range. The consumption of ozone is very dependent of the concentration of contaminants [10,22]. In fact, the increase in the complexity of the mixture promotes a decrease in the pseudo-first order kinetic rates constants (Tables 4 and 5), which translates into a higher residence time required to achieve a complete removal of micropollutant through ozone action. Thus, besides the higher energy consumption to achieve the complete removal of PPCPs in complex mixtures, a reactor with a higher volume would be required that bears increased construction/acquisition and operation costs. Moreover, in real wastewater, other organic

and inorganic species will also be present which might have an influence on the degradation kinetics and, thus, on the processes efficiency and energy consumed. Indeed, the ozonation efficiency is dependent on the complex interplay of the water matrix constituents, which cause inhibitory and promoting effects on PPCPs degradation. This must be kept in mind while projecting the ozonation reactor.

4. Conclusions

Molecular ozone should be the main agent responsible for PPCPs removal in real wastewater since the hydroxyl radical can be scavenged by inorganic species naturally occurring in actual effluents. Herein we followed this rationale and mimicked the exclusive action of molecular ozone in PPCP degradation by lowering the reaction pH. Ozonation reveals its potential to be a suitable solution for the treatment of wastewater containing PPCPs since it allows the complete removal of these compounds in few minutes. The increase of the complexity of the mixtures to be treated can decrease the pseudo-first order kinetic rate constants at a particularly pronounced scale for compounds less prone to ozone oxidation.

Concordantly, the energy consumption required to achieve the complete degradation of PPCPs increases with the complexity of the mixture due to the higher ozone demand for the complete removal of the parent contaminants. These costs would likely be higher if a real municipal or industrial wastewater was considered due to the presence of other elements that can trap molecular ozone leading to higher ozone demands. Thus, the complexity of the water matrices to treat must be taken into consideration while designing an ozonation system. Moreover, if the aim of the wastewater treatment is to recover water for reuse, higher doses of ozone should be needed in the oxidation of PPCPs, given that by-products should be obtained during the ozonation reaction (which can be more difficult to treat by ozone alone).

The obtained data for kinetic rates constant of PPCPs abatement (both in relation to time and TOD) with molecular ozone at pH 3 can be used as a preliminary information of the worst conditions to design a large-scale ozone reactor to operate under natural pH.

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