Spectral characterization of the fluorescent components present in humic substances, fulvic acid and humic acid mixed with pure benzo(a)pyrene solution

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Abstract

The fate of benzo(a)pyrene (BaP), a ubiquitous contaminant reported to be persistent in the environment, is largely controlled by its interactions with the soil organic matter. In the present study, the spectral characteristics of fluorophores present in the physical fractions of the soil organic matter were investigated in the presence of pure BaP solution. After extraction of humic substances (HSs), and their fractionation into fulvic acid (FA) and humic acid (HA), two fluorescent compounds (C1 and C2) were identified and characterized in each physical soil fraction, by means of fluorescence excitation-emission matrices (FEEMs) and Parallel Factor Analysis (PARAFAC). Then, to each type of fraction having similar DOC content, was added an increasing volume of pure BaP solution in attempt to assess the behavior of BaP with the fluorophores present in each one. The application of FEEMs-PARAFAC method validated a three-component model that consisted of the two resulted fluorophores from HSs, FA and HA (C1 and C2) and a BaP-like fluorophore (C3). Spectral modifications were noted for components C2HSs (λex/λem: 420/490–520 nm), C2FA (λex/λem: 400/487(517) nm) and C1HA (λex/λem: 350/452(520) nm). We explored the impact of increasing the volume of the added pure BaP solution on the scores of the fluorophores present in the soil fractions. It was found that the scores of C2HSs, C2FA, and C1HA increased when the volume of the added pure BaP solution increased. Superposition of the excitation spectra of these fluorophores with the emission spectrum of BaP showed significant overlaps that might explain the observed interactions between BaP and the fluorescent compounds present in SOM physical fractions.

Keywords:
Fluorescent excitation-emission matrices
PARAFAC
Humic substances
Fulvic acid
Humic acid
Benzo(a)pyrene

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs), which are compounds formed by the fusion of benzene rings consisting only of carbon and hydrogen, are important environmental pollutants of big concern because many of them are carcinogens and mutagens [1,2]. They originate from a variety of natural and anthropogenic sources. Particular attention has been made on the PAHs with high-molecular mass, such as benzo(a)pyrene (BaP), for their toxicological aspect [3,4]. BaP was reported as an indicator of the presence of other PAHs in different environmental compartments (water, soil, sediments) [5]. It is persistent in the environment, part because of its low bioavailability and because of its strong adsorption onto the soil organic matter (SOM) [6]. This strong interaction with SOM makes it un-degradable and unavailable resulting in soil contamination problems.

Soil organic matter, a key factor in the sustainability of soil, is composed mainly of humic substances (HSs) and nonhumic substances [7,8]. HSs are a complex mixture of several heterogenous aggregates [9]. HSs can be fractioned into humin, a black colored fraction insoluble in water at any pH; the humic acid (HA), black or brown, soluble in basic medium and insoluble in acidic pH (<2), and the fulvic acid (FA), yellowish and soluble in water at any pH [10]. HA is composed of natural polydispersed polyelectrolyte bio-colloids [11,12] and are characterized by the presence of many functional groups such as carboxylic acids, phenols and amines [9]. FA is characterized by small molecular size and large carboxyl group [13]. HA and FA contain also quinone and semi-quinone function groups [14,15]. Studies have shown that soil organic matter is predominant in the sorption of PAHs; it largely controls the fate of these pollutants [16]. PAHs were found to associate with the hydrophobic regions of soil organic matter because they have low solubility in water [17]. Binding affinity, expressed as the partition coefficient (Koc), was found correlated with aromaticity of the organic matter [18]. Thus, the hydrophobicity of the pollutant and the quality of the soil organic matter determine the nature of the interactions...
occurring between them and define the extent of pollutant's bioavailability and toxicity [19,20]. Since SOM has a complex structure that is difficult to characterize, studies have used the physico-chemical properties such as the spectral properties to characterize and define HSs, HA and FA [21], and particularly the fluorescence spectroscopy method [22].

The fluorescence spectroscopy, especially the development of fluorescent excitation-emission matrices (FEEMs) [23,24], have been widely used over the last decade to obtain information on the fluorescent characteristics of organic matter, to determine its origin and to assess its quality in different ecosystems [25–28]. The popularity of this method is due to the fact that it is a highly sensitive and nondestructive method that does not require a large amount of preparation time, the fast data acquisition and the large amount of information on the molecular structure and chemical properties of natural organic matter it provides [29–33]. However, in order to interpret and decompose the FEEMs, chemometric algorithms such as Parallel Factor Analysis (CP/ PARAFAC) are frequently used [34–38]. PARAFAC is an advanced multivariate statistical technique that has been employed in the area of analytical and environmental chemistry; it is often utilized for the analysis of the three-way data sets [39] such as sample with x excitation wavelength y emission wavelength resulted from FEEMs [40–42]. It can identify and quantify the components of a multicomponent system and is able to extract their relative concentration and their pure excitation and emission spectra [43,44]. The combination of FEEMs with the PARAFAC algorithm is widely used to characterize the organic matter from terrestrial origin [22,27,45], aquatic origin [32,42,46]. Several authors have also proven the efficiency of this method to detect PAHs in pure solutions [36], in water samples [34], aqueous motor oil extract and asphalt leachate [34,36,47]. This technique makes it possible to observe the qualitative changes in the dissolved organic matter and the different fluorophores present in the tested samples and to detect changes in their fluorescence intensities [42].

FEEMs-PARAFAC method used for detection and quantification of PAHs in environmental matrices [35,48] can also be applied for understanding the interactions between SOM and organic pollutants, such as BaP, which is crucial for assessing their fate in soil environment. Since it is a novel method, there is currently no information available in literature about the effect of BaP on the spectral characteristics of the fluorophores present in each soil fraction HSs, FA and HA. In this study we combined FEEMs and PARAFAC to (1) determine the spectral characteristics of the fluorophores present in the three physical fractions HSs, FA and HA originating from one soil (2) investigate the effect of the addition of pure BaP solution on the spectral properties of the fluorophores present in HSs, FA, and HA, (3) explore the changes in fluorescence intensities of each fluorophore when the volume of added pure BaP solution increases and (4) clarify the physico-chemical interactions between BaP and the fluorophores present in each soil fraction.

2. Materials and Methods

2.1. Preparation of Pure BaP Solution

BaP was purchased from Sigma-Aldrich (>96%) and was used without further purification. A stock solution of pure BaP (10⁻⁴ M) was produced by weighing the appropriate amount of BaP and dissolving it in ethanol (Carlo Erba HPLC grade). The stock solution was kept in the dark at 4 °C. A 10⁻³ M BaP solution was prepared in ultra-pure water by diluting the stock solution. This solution was used for the experiments with SOM. Triplet concentrations of 10⁻⁵, 2 · 10⁻⁴ and 5 · 10⁻⁹ M of pure BaP solutions were also prepared in ultra-pure water to be used as calibration range to be inserted in the PARAFAC models. Ultra-pure water was taken from an Osmomax water purification unit.

2.2. SOM Extraction and Fractionation

An acidic brown soil sample was collected between 5 and 20 cm in depth from a non-polluted remote area of a high mountain (altitude of 1,657 m) located in the Pyrénées-Orientales department in southern France (42.52649’N; 2.12305’E). SOM was extracted from soil sample in alkaline conditions using an adaptation of Duchaufour and Jacquin [49] protocol, that was later completed by Ratsimbazafy [50]. Briefly, 10 g aliquots of dried (24 h at 105 °C) crushed and homogenized soil sieved through 2 mm mesh, were mixed in PETE bottle with a solution containing 80 mL of 0.1 M NaOH (Sigma-Aldrich) and 120 mL of 0.1 M Na₂P₂O₇ (Sigma-Aldrich) to reach a pH around 13. To obtain a correct homogenization, the bottle was put on a rotating agitator in the dark for 24 h. The mixture was then centrifuged at 3600g for 20 min. The supernatant thus obtained is the humic substances (HSs) fraction. One part of HSs was stored at room temperature in the dark for analysis. The other part was used to separate the FA and the HA fractions. Concentrated HCl (37%, Fulka) was added to HSs, up to pH < 2 and the solution was kept in the dark. After 24 h, a precipitate was observed. This solution was centrifuged at 3600g for 20 min to obtain FA fraction (supernatant) and the HA fraction (precipitate). Prior to analysis, HA was solubilized by adding 50 mL of pure water and agitating till solubilization. The pH of HSs, FA and HA solutions were adjusted to 7.5 ± 0.1. Prior to fluorescence measurements, samples were filtered through a 0.45 μm filters (PTFE-membrane from Sartorius Stedim Biotech).

2.3. Sample Preparation

Reference samples were obtained by preparing five solutions of HSs, FA and HA with different concentrations estimated on their dissolved organic carbon (DOC) contents. Concentrations of DOC were determined using Shimadzu Total Organic Carbon Analyzer VCSN (Shimadzu Corp., Kyoto, Japan). Concentrations of HSs samples were 2.71, 4.71, 7.72, 15.75, 18.22 and 22.11 mg DOC·L⁻¹ of those of FA were 2.693, 3.209, 3.908, 7.779 and 17.48 mg DOC·L⁻¹ and those of HA samples were 6.788, 9.212, 13.5, 17.2 and 20.14 mg DOC·L⁻¹.

As for the experiments with pure BaP, we selected the concentration of each soil fraction having DOC ±7 mg·L⁻¹. For each fraction, triplicates with 3 mL of solution (~7 mg·DOC·L⁻¹) were prepared. 100, 200 and 300 μL of pure BaP solution (10⁻³ M) was added to the first, the second and the third replicates respectively. The triplicates containing the mixture HSs-BaP, FA-BaP and HA-BaP thus obtained constitute three sets of samples that will be named as HSs_BaP, FA_BaP and HA_BaP.

2.4. Fluorescence Spectroscopy

Fluorescence measurements were acquired using a SAFAS f\(x\) spectrofluorometer (SAFAS, Monaco) with a Xenon excitation source (150 W) using 1 cm × 1 cm quartz cell. All further measurements were performed at room temperature (20 °C ± 2 °C). FEEMs were recorded at 270 nm·min⁻¹ scan speed. The excitation wavelengths ranged from 200 to 500 nm at 10 nm steps. Emission wavelengths ranged from 220 to 800 nm at 1 nm interval. Excitation and emission slit widths were set at 10 nm. Raman and Rayleigh diffusions were corrected by subtraction of ultra-pure-water fluorescence from each FEEMs' sample [31]. We have checked that there were no inner filter effects over each sample. Fluorescence intensities are expressed in arbitrary units (a.u.).

2.5. Data Analysis

PARAFAC has been widely described in the literature [41,42,44,52,55] hence, we will briefly describe it. It is applied to a three-way data X that have the trilinear structure such as in the case of FEEM. X, in this case, is a 3-way data cube of dimension I × J × K
and its trilinear decomposition using PARAFAC analysis can be expressed using the following equation

$$X_{ijk} = \sum_{f=1}^{F} a_{ij} f b_{jk} + e_{ijk}$$  \hspace{1cm} (1)$$

The principle of PARAFAC decomposition is minimizing the sum of square of the residual; \((e_{ijk})\) based on a least-squares algorithm which represents some additional residual variation not accounted for by the model. \(X_{ijk}\) is the intensity of fluorescence for the \(i\)th sample at emission wavelength \(j\) and excitation wavelength \(k\). \(a_{ij}\) is the relative concentration of analyte \(f\) in sample \(i\); \(b_{jk}\) is linearly related to the fluorescence intensity of the \(f\)th fluorophore at emission wavelength \(j\). \(e_{ijk}\) is linearly related to the extinction coefficient of analyte \(f\) at excitation wavelength \(k\) and \(e_{ijk}\) represents the sum of the residuals of the matrices. The PARAFAC model was calculated using a homemade program (progmef), developed and provided by R. Redon (PROTEE Laboratory, University of Toulon, France) based on Matlab (TM) software. In order to reduce the effect of diffusion and scatter lines, the Rayleigh and Raman scatter were removed according to Zepp [58]. FEEMs were normalized and the data set was fitted with non-negativity constraint and was run for 100 iterations with initialization by random values for all data sets with a convergence criterion of \(10^{-6}\). A series of PARAFAC model from two to five components were fitted to the data.

The FEEMs of the reference samples of HSs, FA, and HA were modeled in three separate PARAFAC analyses. The FEEMs of the three sets of triplicates containing the mixture with pure BaP solution (HSsBaP, FABaP, HABaP) were also run by PARAFAC.

The results were validated using core consistency diagnostic (CorConDia) [40]. The similarity coefficient, also known as congruence coefficient (\(r_c\)) of the computed and the reference two-dimensional fluorescence spectra was calculated according to [59]:

$$r_c = \frac{\sum ab}{\sqrt{\left(\sum a^2 \sum b^2\right)}}$$  \hspace{1cm} (2)$$

where \(a\) and \(b\) represent the loadings of computed and reference spectrum respectively. In our study, the computed spectra were obtained from the PARAFAC calculations of the three sets of HSs, FA, and HA, and the reference spectra are obtained from the PARAFAC model of the three reference sets of HSs, FA, and HA. This congruence coefficient allows the estimation of the modification of the spectral characteristics of the reference fluorophores from reference sets when pure BaP is added to the soil fractions. An \(r_c = 0.90\) indicates a high level of similarity, values higher than 0.95 indicate that the compared spectra are virtually identical.

### 3. Results and Discussion

#### 3.1. Characterization of the Fluorescent Reference Components in HSs, FA and HA

The appropriate number of components resulting from PARAFAC model was determined by high values of CorConDia and by visual analysis of the spectra of the obtained components. The PARAFAC models tested with 3, 4 and 5 components were excluded because of the low values of CorConDia combined with inappropriate spectral shapes. The best PARAFAC test was obtained from the two-component model. Results showed the contribution of two fluorophores in each soil fraction with a CorConDia of 96%, 94% and 99% for HSs, FA and HA respectively. Fig. 1 shows the spectra of two fluorophores present in the reference HSs, FA and HA. The spectral characteristics of the components C1 and C2 present in HSs, FA and HA showed similarities with previous fluorophores reported in literature (Table 1). Component C1HSs and C1FA from this study had similar spectral characteristics with component 1 found in estuarine system by Singh et al. [51], and in aquatic environments by Stedmon et al. [52] and by Nagao et al [54] and other works listed in Table 1. Component C2HSs and C2FA were found similar to component 4 in estuary from Singh et al. [51] study and component 2 from Stedmon et al. and Stedmon and Markager works found in estuary and sea water respectively [42,55]. C1HA (\(\lambda_{ex}/\lambda_{em}: 350/452\) nm) refers to humic-like component (C-peak) [24] in marine environment and to HA in coral reefs [56]. Component C2HA (\(\lambda_{ex}/\lambda_{em}: 460/(496)\) 520 nm) refers to soil fulvic acid [52] in aquatic environment, to component 2 in whole soil and humin samples [38] to terrestrial HA and lignin derivatives [56] and to Aldrich HA [57].

We used similarity coefficient (\(r_c\)) and visual observations (Fig. 2) to compare the similarity of the spectral characteristics between C1HSs and C1FA and between C2HSs and C2FA. C1HSs and C1FA have similar PARAFAC excitation and emission loading spectra and recorded a congruence coefficient \(r_c = 0.996\) for both excitation and emission (Fig. 2A). The excitation spectra of C1HSs and C1FA recorded a similarity coefficient of 0.968; the peak of C2HSs maximum around 420 nm was broader than that of C1FA maximum at 400 nm (Fig. 2B). The emission spectra of these two components recorded a high similarity coefficient of 0.974 with a common peak at 490 and 487 nm respectively and a second peak at 520 nm for C1HSs which becomes a shoulder at 517 nm for C1FA. Excitation and emission spectra of C1HA had similar shapes comparing to those of C1HSs and C1FA with a red shift around 20 nm (Fig. 2A) (\(\lambda_{ex}/\lambda_{em}: 350/452(520)\) nm). Its emission shoulder at 520 nm is much more apparent than in C1HSs and C1FA (517 nm).

As seen in Fig. 2B, C1HA had less similar excitation spectral loading to those of C1HSs (\(r_c = 0.956\)) and C2FA (\(r_c = 0.927\)). The similarity coefficients of the emission spectral loading of C1HA with the emission spectral loadings of C1HSs and C2FA were 0.966 and 0.942 respectively. The shoulder of C1HA (496 nm) corresponded to common peaks in C1HSs.

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**Fig. 1.** Normalized excitation (dashed line) and emission (solid line) spectral loadings obtained from independent two components (C1 and C2) PARAFAC model from reference fractions HSs, FA and HA.
with added BaP (HSsBaP, FA BaP and HABaP) revealed the presence of 3.2. PARAFAC Decomposition of HSs, FA and HA Containing Pure BaP

three components (Fig. 3B). CorConDia scored 94%, 91% and 41% for C2HSs BaP and C2FA BaP, respectively. The decomposition spectra of C2HSs seem to be a combination of those of C2FA and C2HA. C3FABaP had maxima at 290–380/408–427 nm (rC = 0.999 for the excitation spectra and the emission spectra). The spectral shape of component C3HABaP spectra (λex/λem: (360) 400/492–526 nm) differ from those of HSsBaP and FA BaP with a red shift of around 60 nm. C3HABaP excitation spectrum (maxima at λex: 470 nm) differ from those of C2HSsBaP and C2FA BaP in shape and location and recorded a red shift of around 70 nm. Whereas the emission spectrum of C3HABaP (λem at (495)525 nm), was found similar to those found in HSsBaP and FA BaP having the same peak location but has a narrower shape, their similarity coefficient were 0.928 for C3HSsBaP and 0.926 for C3FA BaP. The shape of the excitation and emission spectra of C3HABaP are slightly modified comparing to those of C3HSsBaP and C3FA BaP and had maxima at λex/λem at 300–370/409–427 nm. The congruence coefficient rC of the excitation spectra of C3HABaP with C3HSsBaP and C3FA BaP are scored 0.958 and 0.950 respectively and those of the emission spectra of C3HABaP with C3HSsBaP and C3FA BaP scored 0.976 and 0.981.

On the other hand, by comparison with the spectral properties of pure BaP (10−5 M) in water, the third fluorophore (C3FABaP; C3HABaP) was identified as BaP. The similarity coefficient rC of the excitation spectral loading of components C3HSsBaP and C3FA BaP with that of pure BaP were 0.995 and 0.991 respectively and those of the emission spectral loadings were of 0.984 and 0.985 respectively. C3HABaP was also identified as BaP having a similarity coefficient rC of 0.972 and 0.988 for the excitation and emission spectral loadings respectively.

Regardless of the high similarity coefficient between the spectral characteristics of C3HABaP and pure BaP, it can be visually noticed that there are some deformations in the shape of C3 spectral loadings in HABaP. That seems to reveal a modification of the spectral characteristics of BaP in HABaP fraction. Thus the presence of BaP affects the spectral characteristics of soil fractions conserving fluorescent feature of pure BaP in HS and FA fractions but not in HA fraction where fluorescence of BaP is modified compared to that of pure form.

Comparison of PARACF spectral loadings of reference components (Fig. 3A) resulting from the separate decomposition of HSs, FA and HA with those resulting from decomposition of HSsBaP, FA BaP and HABaP containing added pure BaP (Fig. 3B) shows that BaP modified the fluorescence features of each fraction differently.

For C1, spectral modifications due to the addition of pure BaP are identical in HSs and FA fractions which have highly similar spectral characteristics as previously mentioned. It was noted that the resulting

(490 nm) and C2FA (497 nm). The peak around 520 nm is common for C1HSs and C1HA while a shoulder was observed for C2FA at similar wavelength (517 nm). On the other hand, excitation and emission spectra of C2HSs seem to be a combination of those of C2FA and C2HA.

3.2. PARAFAC Decomposition of HSs, FA and HA Containing Pure BaP

The best PARAFAC analysis applied to FEEMs of tested soil fractions with added BaP (HSsBaP, FA BaP and HABaP) revealed the presence of three components (Fig. 3B). CorConDia scored 94%, 91% and 41% for PARAFAC decomposition of HSsBaP, FA BaP and HABaP respectively. Despite a weak CorConDia, the three factor PARAFAC model of HABaP was validated because the spectral characteristics of the three components were consistent with those validated in HSsBaP and FA BaP. The decompositions to more than three components did not score a high CorConDia percentage (~40%).

The spectral characteristics of the three fluorophores found in HSsBaP and FA BaP are very similar with similarity coefficients above 0.950. C1HSsBaP and C1FA BaP had their excitation and emission maxima (λex/λem) at 340/430 nm (rC = 0.996 for the excitation spectra and rC = 0.998 for the emission spectra) and C2HSsBaP and C2FA BaP had their maxima and (shoulder) at 400/(494) 525 nm and 400/(495) 526 nm respectively (rC = 0.997 for the excitation spectra and rC = 1 for the emission spectra). C1HSsBaP and C1FA BaP had their λex/λem maxima at 290–380/408–427 nm (rC = 0.999 for the excitation spectra and the emission spectra).

The spectral shape of component C1HA BaP spectra (λex/λem: (360) 400/492–526 nm) differ from those of HSsBaP and FA BaP with a red shift of around 60 nm. C1HA BaP excitation spectrum (maxima at λex: 470 nm) differ from those of C2HSsBaP and C2FA BaP in shape and location and recorded a red shift of around 70 nm. Whereas the emission spectrum of C1HA BaP (λem at (495)525 nm), was found similar to those found in HSsBaP and FA BaP having the same peak location but has a narrower shape, their similarity coefficient were 0.928 for C1HSsBaP and 0.926 for C1FA BaP. The shape of the excitation and emission spectra of C1HA BaP are slightly modified comparing to those of C1HSsBaP and C1FA BaP and had maxima at λex/λem at 300–370/409–427 nm. The congruence coefficient rC of the excitation spectra of C1HA BaP with C1HSsBaP and C1FA BaP are scored 0.958 and 0.950 respectively and those of the emission spectra of C1HA BaP with C1HSsBaP and C1FA BaP scored 0.976 and 0.981.

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Comparison of PARAFAC spectral loadings of reference components (Fig. 3A) resulting from the separate decomposition of HSs, FA and HA with those resulting from decomposition of HSsBaP, FA BaP and HABaP containing added pure BaP (Fig. 3B) shows that BaP modified the fluorescence features of each fraction differently.

For C1, spectral modifications due to the addition of pure BaP are identical in HSs and FA fractions which have highly similar spectral characteristics as previously mentioned. It was noted that the resulting

Table 1

<table>
<thead>
<tr>
<th>Component (this study)</th>
<th>Ex/Em (nm)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component C1HSs</td>
<td>330/433(520)</td>
<td>Component 1 [51]</td>
</tr>
<tr>
<td>C1FA</td>
<td>330/430(520)</td>
<td>Component 1 [52]</td>
</tr>
<tr>
<td>Component C2HSs</td>
<td>420/490–520</td>
<td>Component 4 [51]</td>
</tr>
<tr>
<td>C2FA</td>
<td>400/487(517)</td>
<td>Component 2 [42]</td>
</tr>
<tr>
<td>Component C1HA</td>
<td>350/452(520)</td>
<td>C-peak Humic-like [24]</td>
</tr>
<tr>
<td>Component C2HA</td>
<td>460/(496)520</td>
<td>Component 4 [54]</td>
</tr>
</tbody>
</table>

Fig. 2. Comparison of spectral characteristics of the obtained fluorophores (C1 and C2) from two component PARAFAC model in HSs, FA and HA (normalized spectra).
excitation spectra of C1HSbaP and C1FAbaP were red shifted by 10 nm in comparison with those from the reference data sets C1HS and C1FA. Despite the red shift and the modified shape, the excitation and emission spectral loading of components C1HSBaP scored a congruence coefficient rc = 0.995 and rc = 0.968 with those of the reference C1HS. Comparing the spectral loadings of C1FABaP with those of the reference C1FA, similarity coefficient rc recorded 0.990 for excitation and emission.

Comparing the spectral features of C1HA and C1HAbaP, we noted a modification in the shape of the excitation and emission spectra of C1HAbaP along with a red shift of 50 nm for the λex and 40 nm for λem. The congruence coefficient rc of the compared excitation spectra was rc = 0.910 and that of the emission spectra recorded a lower value (rc = 0.789) that was due to the appearance of the double peak (λem: 492–523 nm) (Fig. 3B).

Spectral characteristics of the excitation and emission loadings of components C2HSbaP and C2FAbaP were also compared to those of C2HS and of C2FA. It was found that the emission spectral loadings of C2HSbaP and C2FAbaP were similar to those of the reference and scored similarity coefficients rc = 0.994 and 0.980 respectively. The intensity of
the peak around 490 nm decreased, while the intensity of the peak around 520 nm increased in C2HSSBaP and C2FABaP. The excitation spectral loadings of C2HSSBaP and C2HSs were less similar and had a similarity coefficient \( r_c = 0.903 \), whereas those of C2FABaP and C2FA showed higher similarity and scored an \( r_c = 0.956 \). It was also noticed that the \( \lambda_{\text{ex}} \) of C2HSSBaP had a blue shift of around 20 nm compared with \( \lambda_{\text{ex}} \) of C2HSs along with a modified shape.

In HABaP fraction, the shape of the excitation spectra of C2HABaP was modified and red shifted by 10 nm compared with that of C2HA. Similarity coefficient of the excitation spectra of C2HABaP and C2HA was weak \( (r_c = 0.814) \). However, the addition of BaP had little effect on the emission spectrum of C2HABaP. It recorded a high similarity coefficient \( (0.980) \) with that of C2HA.

These comparisons demonstrated that the presence of BaP seems to highly influence the fluorescence features of C1 in HA fraction while the fluorescence characteristics of C2 seem to be more affected by BaP in HSs and FA fractions.

### 3.3. BaP Impact on the Fluorophores in Soil Fractions

The influence of BaP on the fluorophores present in soil was studied through the addition of 100, 200 and 300 \( \mu \)L of pure BaP \((10^{-5} \text{ M})\) to 3 mL of HSs, FA and HA. Fig. 4 shows the relative scores of components from PARAFAC in the three tested fractions. The addition of BaP to HSs and FA led to a high increase in fluorescence intensity of C2HSSBaP (slope = 1713.4) and C2FABaP (slope = 1597.1). They had steeper slopes compared to those of C2HSSBaP (340.07) and C2FABaP (133.82). The scores of C2HABaP did not increase with the addition of BaP (slope = 74.372). On the other hand, C1HABaP recorded a high slope (1188.2). These results confirm the influence of BaP addition on fluorescence intensities increase of C2 in HSSBaP and FABaP fractions and of C1 in HABaP fraction. The behavior of C1, identified as BaP, is logically related to the addition of pure BaP with a high increase of relative scores (slope = 1216.2) in HSSBaP fraction. The behavior of C2HSSBaP is similar to the variation of C2HSSBaP (slope = 1713.4). In FABaP data sets, the increase of C1 relative scores is lower (slope = 617.5) than that in HSSBaP. This behavior of C1FABaP shows a moderate variation compared to the high evolution of C2FABaP (slope = 1597.1). The lowest increase of C1 relative scores is observed in HABaP fraction (slope = 332.27) which differs from the high variation of C1HABaP (slope = 1188.2).

This attenuation of C1 fluorescence intensities in FAaP and mainly in HAaP fractions could be due to interactions between BaP and these fractions. As reported in previous studies, HA was found to be a fluorescent quencher that can reduce the fluorescence intensity of PAHs such as phenanthrene, pyrene, anthracene [48], naphthalene [60] and fluoranthene [61]. So quenching effect could have caused the attenuation of...
the fluorescence intensities of C1HA\textsubscript{BaP} in HA fraction in our study. Perhaps this phenomenon could have also occurred in a less intensive way in F\textsubscript{A\textsubscript{HA} Pur} fraction.

By taking into consideration the higher variations of fluorescence intensity of C\textsubscript{2}HS\textsubscript{s}, C\textsubscript{2}FA, and C\textsubscript{1}HA compared to those of C\textsubscript{3}HS\textsubscript{s}, C\textsubscript{3}FA, and C\textsubscript{1}HA, it is possible to interpret these results as fluorescence resonance energy transfer (FRET). Superposition of the excitation and the emission spectra of pure BaP and those of the reference components present in HS\textsubscript{s}, FA and HA were carried out because the existence of overlaps between emission spectra of one component (energy donor) with the excitation spectra of another (energy acceptor) might induce energy transfer that in turn influences the fluorescence intensities. The fluorescence intensity of the energy donor shall decrease while that of the acceptor will increase. The superposition showed that the excitation spectra of components C\textsubscript{1}HS\textsubscript{s} and C\textsubscript{3}FA completely covers the emission spectra of pure BaP (Fig. 5A and B). The energy from the emission of BaP (donor) might have been transferred to the excitation of C\textsubscript{2}HS\textsubscript{s} and C\textsubscript{2}FA (acceptors). It is also noted that the emission spectra of pure BaP overlaps the end of the excitation spectra of C\textsubscript{1}HA, and the beginning of the excitation spectra of C\textsubscript{1}HA (Fig. 5C). As only C\textsubscript{1}HA\textsubscript{BaP} fluorescence intensities increased (Fig. 4), this might propose that C\textsubscript{1}HA gained energy from the emission of pure BaP.

4. Conclusion

We studied by means of FEEMs-PARAFAC method, the spectral characteristics of the fluorescent components present in the SOM physical fractions HS\textsubscript{s}, FA and HA originating from a single soil sample. Then we investigated their spectral properties upon the addition of pure BaP solution to obtain new information regarding the interactions of BaP with these fluorophores.

HS\textsubscript{s} and FA fractions had one component (C\textsubscript{1}) highly similar. Upon addition of pure BaP solution component C\textsubscript{2}HS\textsubscript{s} and C\textsubscript{2}FA recorded similar spectral modifications.

Increasing the added volume of pure BaP solution allowed us to evaluate the variations of the scores resulting from PARAFAC model. These scores variations were also similar for HS\textsubscript{s} and FA fraction. We noticed that the scores of C\textsubscript{2}HS\textsubscript{s} and C\textsubscript{2}FA increased when the volume of added pure BaP solution increased.

The fluorophores present in HA fraction did not show high similarity with those present in HS\textsubscript{s} and FA except for the emission of C\textsubscript{1}HA that was quite close to those of C\textsubscript{2}HS\textsubscript{s} and C\textsubscript{2}FA. The addition of pure BaP solution resulted in spectral modification of component C\textsubscript{1}HA and when the volume of BaP increased, the scores of this fluorophore increased as well.

The superposition of the excitation spectral loadings of C\textsubscript{1} and C\textsubscript{2} with the emission spectra of BaP in this study showed that BaP might be an energy donor and C\textsubscript{1}HS\textsubscript{s}, C\textsubscript{2}FA, and C\textsubscript{1}HA might be energy acceptors. Further complementary analysis using time-resolved fluorescence technique could support these observations.

This work showed that MEEFs-PARAFAC method can be applied for monitoring the quality of soils and for evaluating of the fate of polycyclic aromatic hydrocarbon such as benzo[a]pyrene in the humic substances, fulvic acid and humic acid.

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References


Fig. 5. Superposition of the normalized excitation spectra obtained from a two-component PARAFAC model of reference HS\textsubscript{s}, FA and HA fractions and the normalized emission spectra of pure BaP.

