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Treatment of algae-rich water by coagulation combined with an adsorbent based on sewage sludge

Co-Authors : RAKOTONIRINA Miora[1,2], ZHANG Weijun[2], ANDRIANARY Philippe[1]

[1]Ecole Doctorale en Sciences et Techniques de l'Ingénierie et de l'Innovation, Equipe d'Accueil Doctorale Valorisation des Ressources Propres, Ecole Supérieure Polytechnique d'Antananarivo, Madagascar

[2]School of Environmental Studies, China University of Geosciences Wuhan, China

Corresponding Author : RAKOTONIRINA Miora

Address : Ecole Doctorale en Sciences et Techniques de l'Ingénierie et de l'Innovation (ED-STII), École Supérieure Polytechnique d'Antananarivo, BP 1500, 101 Antananarivo, Madagascar

e-mail : miorakotonirina@gmail.com

Abstract

This work aimed to investigate the performance and the capacity of combined chemical coagulation and sludge based carbon (SBC) adsorption process on algae-rich wastewater treatment by evaluating the optimization of process control and algae organic matter changes. The results showed that the pH value and the presence of excess negative charge affect the efficiency of the coagulation-adsorption process on algae removal by restabilization of algae cells. An increase in the average algal floc size was observed during the coagulation process, indicating a significant enhancement of algal cells aggregation by the charge neutralization mechanism. Three dimensional excitation emission matrix fluorescence (3D-EEM) showed that the best removal efficiency of tryptophan proteins, fulvic acids and humic acids occurred under combined coagulation-adsorption process rather than single coagulation process and at optimal condition.

Keywords

Algae organic matter (AOM); coagulation-adsorption; optimization; sludge based carbon (SBC)

Abbreviation lists

3D-EEM : Three Dimension-Excitation Emission Matrix

AC: Activated Carbon

AOM: Algae Organic Matters

COM: Cellular Organic Matter

DOC: Dissolved organic Carbon

DOM: Dissolved organic matter

E_m: Emission

EOM: Extracellular Organic Matter

E_x: Excitation

FA: Fulvic Acid

FRI: Fluorescence Regional Integration

HA: Humic Acid

MA: *Microcysits aeruginosa*

NOM: Natural Organic Matter

NTU: Nephelometric Turbidity Units

PAC: Polyaluminum Chloride

PMT: Photomultiplier Tube

SBC: Sludge Based Carbon

SMP: Soluble Microbial by Product

TOC: total organic compound

1. Introduction

A continuing worldwide problem for drinking water treatment is the presence of algae in surface water supplies as a result of eutrophication. Overgrowths of algae caused by discharge of wastewater rich in nitrogen and phosphate in water sources such as lakes and rivers can generate a variety of algae organic matter (AOM), including extracellular organic matter (EOM) and cellular organic matter (COM) [1]. Polysaccharides, nitrogen-containing compounds, organic acids, lipids and fatty acids are all found in AOM from various matrix [2]. The presence of AOM in drinking water supply would cause significant disturbances in water treatment process including clogging of filters, increasing coagulant demand, residual turbidity, increasing filter backwash water requirements, increasing disinfection by-product formation, producing unpleasant tastes and odors, producing toxins, and increasing the microbial regrowth potential in distribution systems [3] [4]. In order to minimize these undesirable effects, it is essential to reduce the concentration of algae cells and AOM in water. However, algal biomass is very difficult to be separated from water with standard separation technology because AOMs are characteristic of a highly hydrated property [5]. In addition, algae properties such as their low specific density and size, negative surface charge, motility, and growth phase affect their separation from water which pose a serious challenge to most water treatment technologies [6] [7] [8]. They are also capable of restoring their negative surface charge after coagulation, by transferring ions across their cell membrane [9]. Dong et al. have been illustrated these issues in their previous work with centrifugation and pressurized filtration of algae [10]. Several approaches have been proposed to improve the algae removal from water for example dissolved air flotation and ultrafiltration methods, electro-coagulation-flotation and hydrodynamic cavitation processes which all have been proven to be effective but their application is restrained due to their high cost [11] [12]. Coagulation-flocculation has been shown as an efficient and practical process for algae removal, although care must be taken to remove these organisms without disrupting the cells, as this may release liver or nerve toxins [13]. Addition of traditional chemical coagulants such as inorganic salt coagulants and organic polymers have long been used to destabilize particles for drinking water treatment and have been recently studied for algae harvesting [14]. They can agglomerate microalgae cells to form large flocs through charge neutralization and bridging, which can be more easily separated from the water by flotation or sedimentation [15]. Nevertheless, the traditional Al and Fe coagulations treatment can hardly achieve satisfactory removal of algae cells due to their negative

surface charge, high motility, diverse morphology, and low specific density [16]. Moreover, with the increased variability on concentration and composition of AOM in water, the efficiency of this conventional coagulation process was significantly reduced. Henceforth the necessity to the advanced coagulation processes by optimizing the process control mainly the coagulant dose and the pH, evolving more efficient coagulant as well as coupling coagulation process with other water treatment technologies [13]. Nowadays, there is a growing interest in the use of pre-hydrolyzed coagulants polyaluminum chloride (PAC) due to its several benefits over conventional inorganic coagulants in higher organic matter removal efficiency such as the ability to form more robust flocs, lower aluminum residuals in treated water, reduced sludge volumes, insensitive on change of temperature and pH and high charge neutralization property [17]. Previous studies have shown that activated carbon AC can remove micro pollutants, organic chemicals, tastes, odors, and algal toxins depending on the carbon dose, type of carbon, toxin level and organic matrix [18]. Powder AC is more effective than granular AC especially for raw water containing algogenic organic matter from cyanobacteria [19]. Sludge based carbon (SBC) adsorbent is recently receiving a lot of attention to a prevalent application due to its ability to absorb a wide variety of organic compounds from sewage as well as the economic feasibility and its harmlessness of use. Parmila Devi et al. used sludge-based adsorbents to remove pollutants such as heavy metals, dyes, miscellaneous compounds from sewage [20]. Waste sewage sludge can be converted into porous activated carbons through anaerobically pyrolysis and the obtained SBCs can be catalyzed through chemicals like potassium hydroxide KOH, sodium hydroxide NaOH, zinc chloride $ZnCl_2$ which can increase their specific surface area, pore volume and distribution [21].

In conjunction to the abovementioned scenario, the present work investigated the performance and the capacity of combined chemical coagulation and SBC adsorption process on algae-rich wastewater treatment; optimization of process control and algae organic matter change were evaluated. The specific objectives are (1) to study the influence of pH and the presence of different ions on coagulation efficiency and to achieve optimal control by jar test; (2) to study algal floc size changes using the Malvern Mastersizer equipment; (3) to explore the efficiency of the adsorption on residual organic matter by batch method, (4) to analyze the evolution of the composition of organic matter using a 3D-EEM fluorescence spectrometer.

This work will adopt low-cost coagulation-adsorption process and provide certain significance reference for algae rich water emergency treatment.

2. Materials and methods

2.1 Materials

2.1.1 Algae cells

The raw water used in these experiments is algal containing water with high concentration of *Microcysits aeruginosa (*MA) cells growth in BG-11 medium method adopted by Zhang et Al [16]. The basic properties of the raw water with high concentration of *Microcysits aeruginosa* cells are represented in table 1.

2.1.2 Chemical reagents

Hydrogen chloride HCl, sodium hydroxide NaOH, Calcium chloride $CaCl_2$, sodium bicarbonate $NaHCO_3$, potassium phosphate KH_2PO_4, Sodium sulfate Na_2SO_4 and zinc chloride $ZnCl_2$ were purchased from Sinopharm Chemical Reagent Co., Ltd. China. A commercial polyaluminum chloride PAC used as coagulant was purchased from Beijing. Deionized water was used to produce stock solution of the coagulant (20% w/w). The properties of PAC used during this experiment is shown in the table 2.

2.1.3 Adsorbent

Waste activated sludge obtained from Beixiaohe waste water treatment plant WWTP in Beijing was used to produce the sludge based carbon adsorbent.

2.2 Experimental procedure

2.2.1 Algae-rich wastewater coagulation process

The stability of the algae was selected for coagulation beaker experiment. Series of jar tests were carried out to determine the optimal operating conditions for algae cells and AOM removal by: addition of different dose of PAC 20mg/L-120mg/L, variation of pH at 5 to 10 with 0.1 N solution of hydrochloride acid HCl and sodium hydroxide NaOH. A 200 mL of raw algae rich wastewater was poured into six 500 mL glass beakers and treated under the following conditions: addition of PAC under fast mixing of 200rpm for 2minutes30 followed by slow mixing for 10minutes at 40rpm. Settling time of 45minutes after which the measurements on turbidity, TOC and 3D-EEM were conducted. By determining the turbidity value, the PAC optimal dosage is determined (the lowest turbidity value). At the optimal dosage, calcium ion Ca^{2+} and bicarbonate ion HCO_3^- with different dosages 10mg/L to 100mg/L and 100mg/L to 1000mg/L respectively were added.

2.2.2 AOM adsorption process

2.2.2.1 Preparation of sludge based carbon (SBC)

The method described by Hadi et Al was adopted in this work for the preparation of SBC [22]. The sludge cake obtained after suction filtration was dried in drying oven at 105 ℃ for reaching constant weight, then grinded, sieved, collected. The sludge powders were activated chemically with $ZnCl_2$ solution by mixing them in chosen ratio for 24h at ambient temperature. The mixing solution were carbonized at a temperature from 20℃ to 600℃ with the heating rate set as 10 ℃/min in a tubular furnace under protection of N_2 atmosphere. The obtained SBC particles were naturally cooled until their temperature reached room temperature and were washed carefully with a solution of 3M HCl for 2 min, and then washed with deionized water until reaching neutral pH. Finally, they were dried for 24h at 105℃, crushed manually and sieved into a uniform size through 100mesh for further characterization and use in algae-rich water treatments. The chemical composition and the specific surface area and pore distribution of the obtained SBC are given in the table 3 and table 4 respectively.

2.2.2.2 AOM adsorption experiments

The SBC powder with controlled dosages in the range from 100mg/L to 600mg/L was added to 50ml of supernatant obtained after optimized chemical coagulation process under agitation for 4hours. Then, all samples were settled for 30mn and filtered for further turbidity, DOC and 3D-EEM measurements. Variation of pH 5-10; addition of different doses of calcium ion Ca^{2+} (10mg/L to 100mg/L), sulphate ion SO_4^{2-} (100mg/L to 1000mg/L) and phosphate ion PO_4^{3-} (100mg/L to 1000mg/L) were conducted prior optimal SBC dose addition.

2.2.3 Sludge floc size

A small-angle light scattering instrument (Malvern Mastersizer 3000, UK) was used to measure dynamic floc size. Flocs were monitored by drawing the suspension with a micropipette over the optical unit of the Mastersizer and back into the jar by a peristaltic pump at a flow rate of 1.5 L/h.

2.2.4 AOM analysis using 3D-EEM

The AOMs changes in algae rich water were determined using 3-Dimension fluorescence excitation-emission matrix spectrums (3D-EEM, HitachiF-4500) measurement, with an excitation E_x range from 200 to 400 nm and an emission E_m range from 220 to 550 nm. The spectra were recorded at a scan rate of 12,000 nm/min. Fluorescent organic matter exhibits different peaks at known E_x and E_m wavelengths: peaks between $\lambda_{Ex/Em}$(nm)=200-250/280-330 and $\lambda_{Ex/Em}$(nm)=200-250/330-380 are related to tyrosine- like and tryptophan-like simple aromatic proteins, peaks between $\lambda_{Ex/Em}$(nm)=200-250/380-550 and $\lambda_{Ex/Em}$(nm)=250-400/280-380 represents respectively

fulvic acid-like materials and soluble microbial byproduct-like material, peak at $\lambda_{Ex}/_{Em}$(nm)=250-400/380-550 is related to humic acid-like organics [23] [24]. All samples were filtered through 0.45μm membrane and diluted 5 times prior to the measurement.

2.2.5 Other indicators

pH was measured by pH meter with glass electrode method; turbidity expressed in nephelometric turbidity units NTU was measured by turbimeter HACH2100N with an infrared diode at wavelength 890nm; a torch TOC analyzer (Teledyne Tekmar, USA) was used for DOC determination. All samples were filtered through 0.45μm sterilized membranes prior to analysis.

3. Results and discussion

3.1 Effect of chemical coagulation with PAC on turbidity and DOC

The figure 1 present the effect of chemical coagulation on turbidity and DOC by: (a) different dosage of PAC 20mg/L-120mg/L, (b) pH adjustment 5-10, (c) addition of different dosage of Ca^{2+} (10mg/L-100mg/L), (d) addition of different dosage of HCO_3^- (100mg/L-1000mg/L). The optimal coagulation performance occurred at the coagulant dose that related to the complete charge neutralization with the lowest settled water turbidity 2.81 NTU. The figure 1(a) showed that the DOC removal efficiency of MA cells was improved with the increase in the PAC dosage from 20mg/L to 120mg/L. The figure 1(b) revealed that at the optimum pH=7, turbidity and DOC reached the minimum 0.303NTU and 8.60mg/L respectively while it increased with further increased in pH. Increase of pH promoted to the deprotonation of organic substances so that negatively charged species were increased, consequently it decreases the removal rate of algal cells and organic matters. It was very probable that the DOC removal at the optimum pH was completely ascribed to adsorption on precipitated aluminum hydroxide in which the organic matters are less soluble and are easier to remove with coagulation. A continual decrease in turbidity and DOC with an increase dose in calcium ion Ca^{2+} respectively from 178.2NTU to 0.88NTU and from14.6mg/L to 7.6mg/L was detected on the figure 1(c). This phenomenon is a sign that enmeshment or sweep coagulation is the main coagulation mechanism happening. But also probability of some primary charge neutralization and polymer bridging occurring instantaneously because calcium ion Ca^{2+} is able to support charge neutralization and decrease the repulsive force between algae cells particles in suspension, serving coagulation. Depicted in the figure 1(d), turbidity and DOC removal decreased with increased in dosage of HCO_3^-. Increase in dosage of HCO_3^- produced surplus negative charge which disadvantaged the charge neutralization and bridging, resulting restabilization of algae cells system. Also increase in HCO_3^- dose promoted in increase of water alkalinity and the increased in turbidity was due to precipitation. Zhao et al. affirmed in their previous work that t high alkalinity, the complex of aluminum produced by PAC prehydrolysis carries less positive charge decreasing the removal rate of algal cells [25].

3.2 Effect of combined process of optimized chemical coagulation and sludge based carbon adsorption on turbidity and DOC

The supernatant used during this experiments was from the optimized coagulation process (PAC dose 80mg/L, pH 7). The figure 2 showed the effect of the combined chemical coagulation and

SBC adsorption process on turbidity and DOC with: (a) different dosage of SBC 100mg/L-600mg/L, (b) pH adjustment 5-10, (c) different dosage of Ca^{2+} (10mg/L-100mg/L), (d) different dosage of PO_4^{3-} (100mg/L-1000mg/L) and (e) SO_4^{2-} (100mg/L-1000mg/L). As depicted in figure 2(a), turbidity and DOC removal were enhanced by increasing SBC dosage which reached the minimum 1.51NTU and 2.04mg/L respectively at SBC dose 600mg/L. Increasing the dose of SBC results on the availability of significant vacant surfaced sites which increased the adsorbent surface area. Observed in the figure 2(b), as the pH increased, Turbidity and DOC experienced a reduction process and a subsequent rising process, and met their minimal values at the optimal pH=8. Referred to the figure 2(d) turbidity removal increased with increased dose of PO_4^{3-} ion while the DOC removal decreased. However, shown in the figure 2(c) and figure 2(e) respectively, with increased dose of Ca^{2+} and SO_4^{2-} ion concentration, no big difference in turbidity and DOC changes were detected. The figure 2 illustrate clearly a significant enhancement of the turbidity and DOC removal after the combined chemical coagulation and sludge based carbon adsorption treatment process.

3.3 Change in floc size under chemical coagulation

The properties of floc are very important impact factors in coagulation for the efficient removal of aggregated particles [26]. As an inorganic polymeric coagulant, not only the charge neutralization was in charge of coagulation process but also the bridging mechanism, which can be specified by floc size characterization [13]. Figure 3 showed the variations of average floc size $d_{(0.5)}$ of the settle floc under chemical coagulation: (a) PAC dosage (20mg/L-120mg/L); (b) pH 5-10; (c) Ca^{2+} dosage (10mg/L-100mg/L); HCO_3^- dosage (100mg/L-1000mg/L) (PAC dosage 80mg/L for (b), (c), (d)). As can be seen in figure 3(a), with increase dosage of PAC, the algae floc size was in the range from 8.02μm to 25.8μm, which reached the maximum at the dosage of 80mg/L, a dosage related to the complete charge neutralization, formed fibers which attached to several colloids, taking and binding them together. Regarding variation of pH from 5 to 10, the largest floc size was detected at the optimal pH value 7 shown by the figure 3(b). Presented in figure 3(c), with increase dose of Ca^{2+}, the algae floc size obviously increased from 107μm to 123μm resulting in precipitation, formation of large amorphous hydroxide flocs as hydrous metal oxides and most of algae cells get trapped in the settling hydrous oxide flocs which lead to the algae cells aggregation and bridging improvement. The figure 3(d) confirmed clearly that the addition of HCO_3^- produced surplus negative charge which affected the charge neutralization and the bridging because the dose of

coagulant is not enough resulting to the restabilization of algae cells system. With the increase dose of HCO_3^-, the algae floc size dropped down from 91.5µm to 80.5µm.

3.4 Change in AOMs: 3D-EEM analysis

3.4.1 Change in AOMs during coagulation process

Figure 4 revealed the effects of PAC coagulation on 3D-EEM profile of AOMs in algae rich water with: (a) different dosage of PAC, (b) pH adjustment, (c) different dosage of Ca^{2+}, (d) different dosage of HCO_3^-. Three fluorescence peaks were detected during chemical coagulation process: the peak I at $\lambda_{ex/em}$=280/350nm indicate soluble microbial byproduct SMP. The peak II at $\lambda_{ex/em}$=245/425nm and peak III at $\lambda_{ex/em}$=350/410nm are associated with Fulvic acid FA and Humic acid HA respectively. The changes in AOMs fluorescence intensities during chemical coagulation process were given in the figure 5: (a) PAC dosage (20mg/L-120mg/L); (b) pH 5-10; (c) Ca^{2+} dosage (10mg/L-100mg/L); HCO_3^- dosage (100mg/L-1000mg/L) (PAC dosage 80mg/L for (b), (c), (d)). The figure 5(a) displayed that the fluorescence intensities of all peaks degraded with increased dose of PAC. For pH adjustment, the figure 5(b) clarify that the best removal efficiency of AOM occurred at optimum pH=7 which allows the function of soluble AOM-Al complexes that link to each other, thereby forming large insoluble bridge complexes microflocs that also act as nuclei for macrofloc development. However, qualitatively, as pH increased, the humic substances become more ionized because the carboxyl groups lost protons which decreased the positive charge of PAC consequently decreasing the binding strength of AOMs [9]. That mechanism makes them difficult to remove by coagulation. The figure 5(c) showed that as the concentration of calcium ion increased, an effective removal of SMP are detected while the removal ability of the FA and the HA are limited. For the addition of HCO_3^- with different concentration, an obvious change in fluorescence intensities were detected in the figure 5(d). The fluorescence intensities for SMP, FA and HA increased with increased doses of HCO_3^- from 485.6nm, 686.4 nm and 700.4nm to 7383nm, 1957nm and 890nm respectively. It exhibited the same phenomena as the pH adjustment due to the increase of the alkalinity. All these results showed that coagulation can effectively remove tryptophan protein SMP but the removal ability of FA and HA are limited. The good SMP removal by chemical coagulation with PAC may be attributed to its strong complex and adsorption capacity. Charge neutralization may also involve an important role in SMP removal as it belongs to macromolecular colloid substances. As HA molecules contain many functional group such as carboxyl group, hydroxyl group, carbonyl group, quinone and methoxy group which

have affinity to interact with many substances, they are always presented in water environment in the form of complexes with metal ions.

3.4.2 Change in AOMs during combined chemical coagulation and sludge based carbon process

Figure 6 characterized the EEM profile of AOMs in algae rich water under combined chemical coagulation and SBC adsorption process with: (a) different dosage of SBC 100mg/L-600mg/L, (b) pH adjustment 5-10, (c) different dosage of Ca^{2+} (10mg/L-100mg/L), (d) different dosage of PO_4^{3-} (100mg/L-1000mg/L) and (e) SO_4^{2-} (100mg/L-1000mg/L). It was obvious that 3 fluorescence peaks were detected during the combined coagulation-adsorption process: the peak I at $\lambda_{ex/em}$=280/350nm indicate soluble microbial byproduct SMP, the peak II at $\lambda_{ex/em}$=245/425nm and peak III at $\lambda_{ex/em}$=350/410nm are associated with Fulvic acid FA and Humic acid HA respectively. The figure 7 illustrated the NOMs fluorescence intensity after the combined chemical coagulation and SBC adsorption process: (a) different dosage of SBC 100mg/L-600mg/L, (b) pH adjustment 5-10, (c) different dosage of Ca^{2+} (10mg/L-100mg/L), (d) different dosage of PO_4^{3-} (100mg/L-1000mg/L) and (e) SO_4^{2-} (100mg/L-1000mg/L). It is shown in the figure 7(a) that with increasing SBC dosage from 100mg/L to 600mg/L the fluorescent intensities of AOMs mainly included SMP, FA and HA degraded from 654.9nm to 77.3nm, 1246nm to 59nm and 1530nm to 89.2nm respectively. It may be due to the increased adsorbent surface area and the availability of more vacant surfaced sites. The figure 7(b) displayed the influence of pH in range of 5 to 10 on the adsorption behavior of SBC for AOMs. pH is a predominant parameter in the adsorption process and directly affects the state of charge of the adsorbent and the organic compound. It can be seen clearly that the removal efficiency increased slightly when the pH increased from 5 to 8 and dropped sharply with the increase of pH higher than 8. At pH<7, SMP, FA and HA are inhibited in the acidic medium and this may be attributed to the the presence of H^+ ion competing with these AOMs for the adsorption sites leading to the strong adsorption efficiency. At pH>8, SMP, FA and HA are partially ionized and their negatively charged ions are repelled by the negatively charge SBC surface. This low AOMs removal at high pH may be also be a result of the competition between the OH^- ions and the AOMs anions. While, AOMs removal were enhanced after the combined process under addition of Ca^{2+}, PO_4^{3-}, SO_4^{2-} ions. Moreover, the figure 6 undoubtedly confirmed that all peaks began less intense after the combined process.

4. Conclusion

In this study, the efficiency of algae cells and algae organic substances synchronous removal by combined PAC chemical coagulation and SBC adsorption were assessed. The results revealed that pH values and addition of some ions significantly affected the removal efficiency of algae cells and AOMs. Tryptophan protein related to microbial activity SMP ($\lambda_{ex/em}$=280/350nm), Fulvic acid FA ($\lambda_{ex/em}$=275/425nm) and Humic acids HA ($\lambda_{ex/em}$=350/410nm) were detected by 3D-EEM fluorescence spectrometry analysis. The best removal efficiency of AOM occurred at optimal dose and at neutral pH in which the function of soluble AOM-Al complexes connected to each other, forming large insoluble bridge complexes microflocs that also act as nuclei for macroflocs development. Qualitatively, coagulation can affectively remove tryptophan protein but the removal ability of humic substances FA and HA were limited. It may attribute to the strong complex and adsorption ability of the tryptophan protein. The SBC adsorption combined with the chemical coagulation process was highly efficient for the removal of the remaining tryptophan protein, fulvic acid and humic acid. They were easily removed by adsorption onto SBC due to their high molecular weight.

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7. Tables

Table 1: Basic properties of the raw water with high concentration of *Microcysits aeruginosa* cells

Table 2: Properties of PAC coagulant

Table 3: Chemical composition of SBC

Table 4: Specific surface area and pore distribution of SBC

Table 1: Basic properties of the raw water with high concentration of *Microcysits aeruginosa* cells

Indicator	Turbidity (NTU)	pH	OD680	TOC (mg/L)	Zeta potential (mV)	$D_{0,5}$/µm	UV_{254}
Value	460	9.54	2.223	83.24	-63.4	21.3	0.73

Table 2: Properties of PAC coagulant

	pH	Insolubility (%)	Basicity (%)	Free acid (mg/L)	ρ(g/ml)	Zeta potential (mV)
PAC	4.15	0.112	55.53	-	1.2268	43.1

Table 3: Chemical composition of SBC

	CIS	NIS	OIS	Al2P	Si2P	Ca2P	Fe2P
SBC	60.93	3.82	27.89	4.51	2.68	0.15	0.03

Table 4: Specific surface area and pore distribution of SBC

	BET (m^2/g)	External surface (m^2/g)	Micropore area (m^2/g)	Micropore volume (m^3/g)
SBC	641.56	562.49	79.07	0.002851

8. Figures

Figure 1. Effect of chemical conditioning on turbidity and TOC with: (a) different dosage of PAC, (b) pH adjustment, (c) addition of different dosage of Ca^{2+}, (d) addition of different dosage of HCO_3^- (PAC dosage 80mg/L for (b), (c) and (d)).

Figure 2. Effect of the combined chemical conditioning and SBC adsorption process on turbidity and DOC with: (a) different dosage of SBC, (b) pH adjustment, (c) addition of different dosage of Ca^{2+}, (d) addition of different dosage of PO_4^{3-} and (e) SO_4^{2-} (PAC dosage 80mg/L, pH=7, SBC dosage= 400mg/L for (b)(c)(d)(e))

Figure 3. Algae floc size variation under chemical coagulation: (a) PAC dosage (20-120mg/L); (b) pH 5-10; (c) Ca^{2+} dosage (10-100mg/L); HCO_3^- dosage (100-1000mg/L) (PAC dosage 80mg/L for (b), (c), (d))

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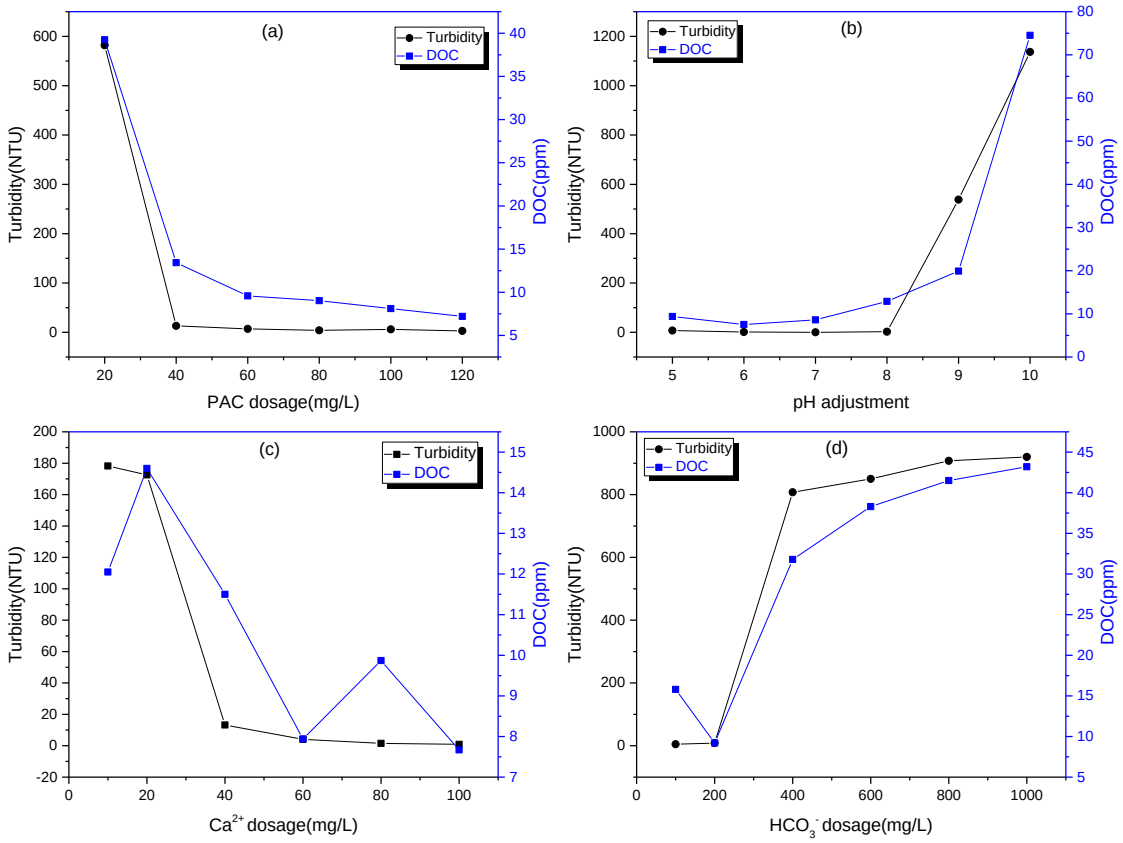

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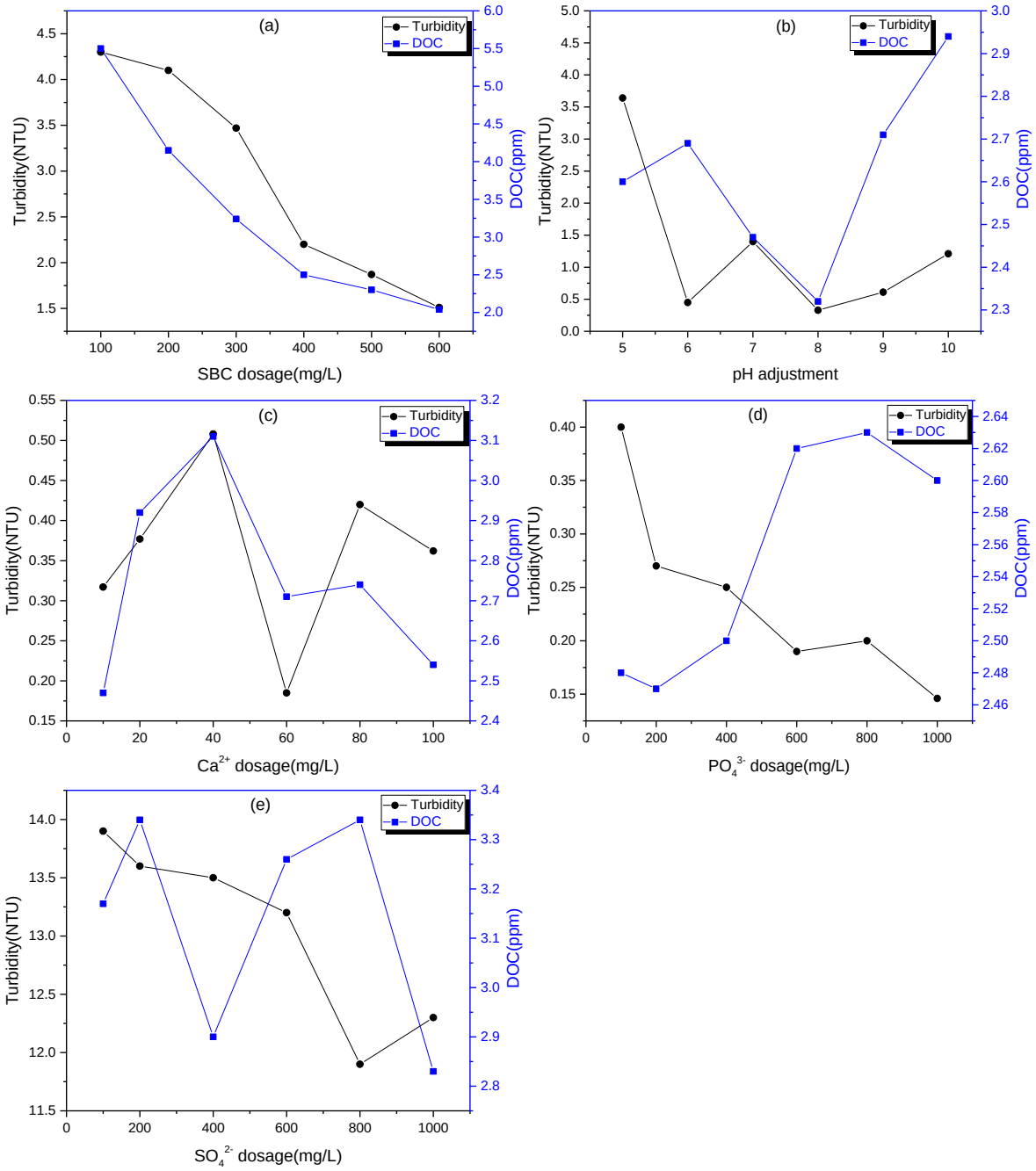

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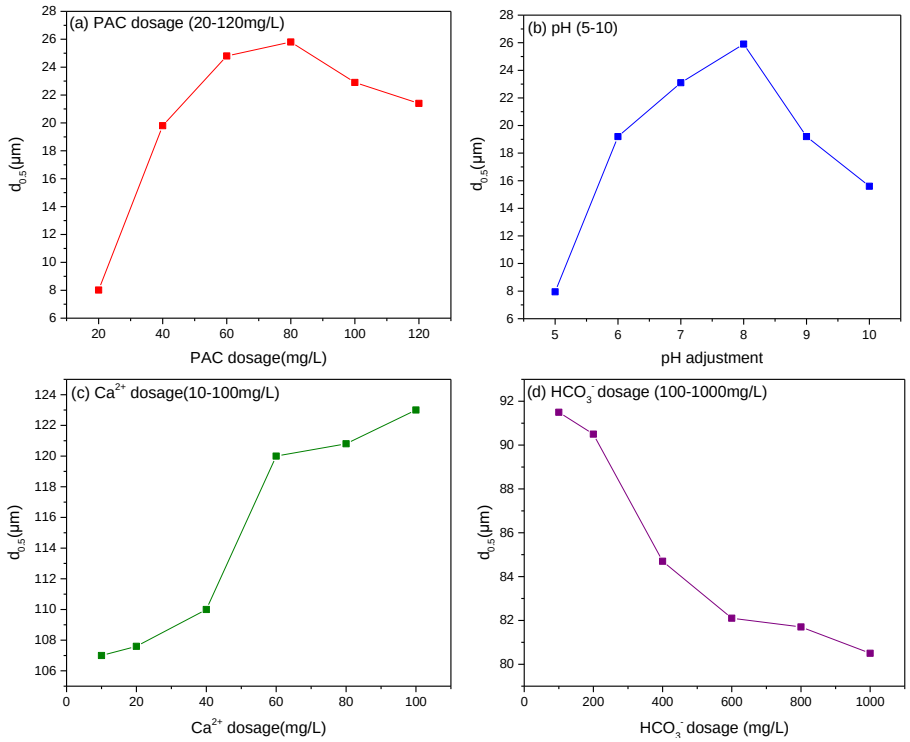

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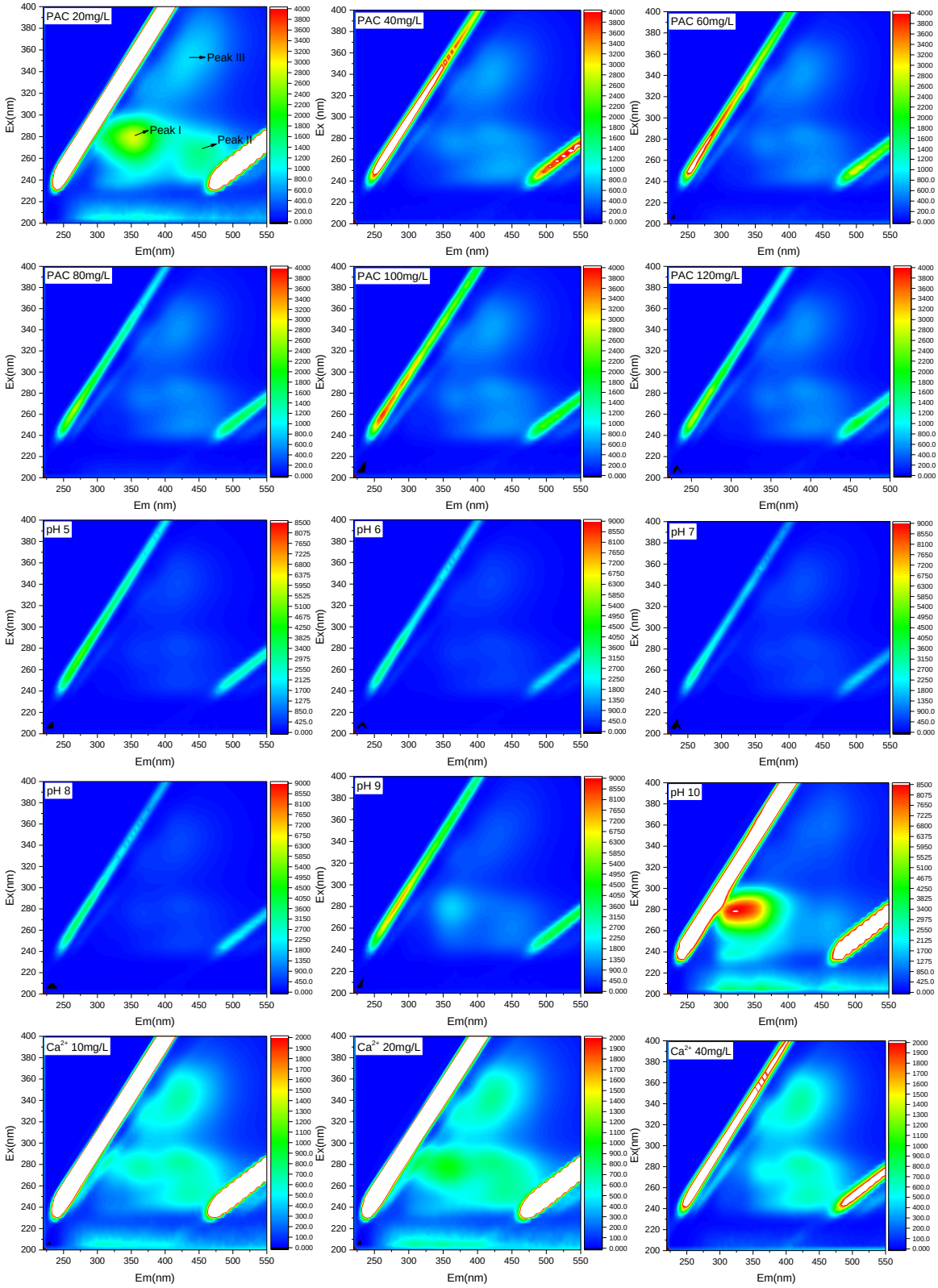

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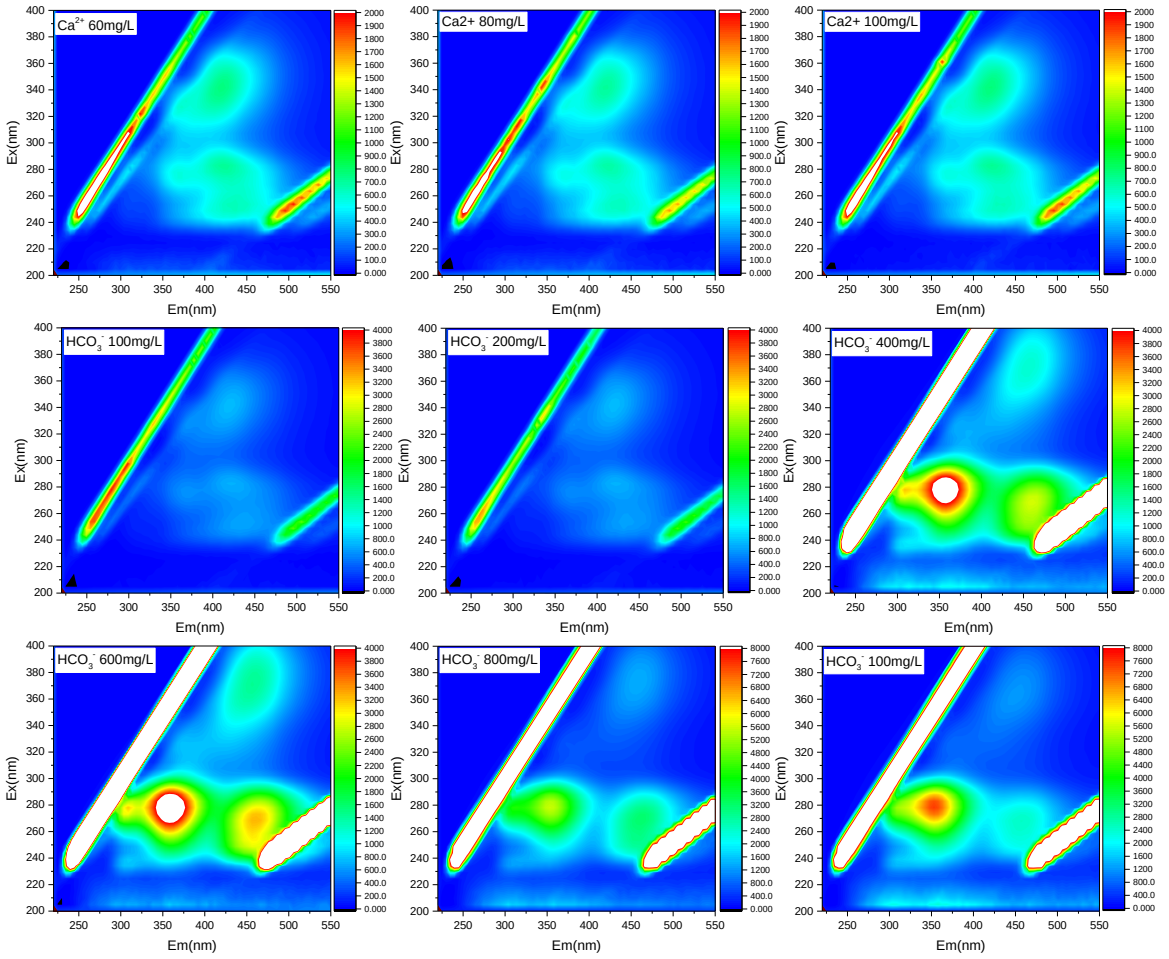

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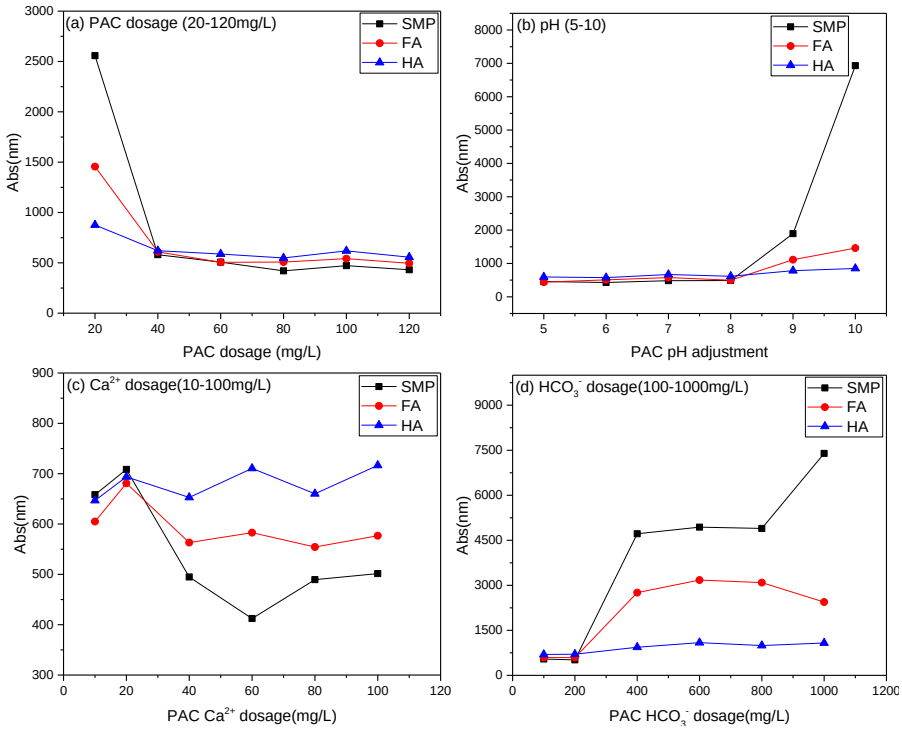

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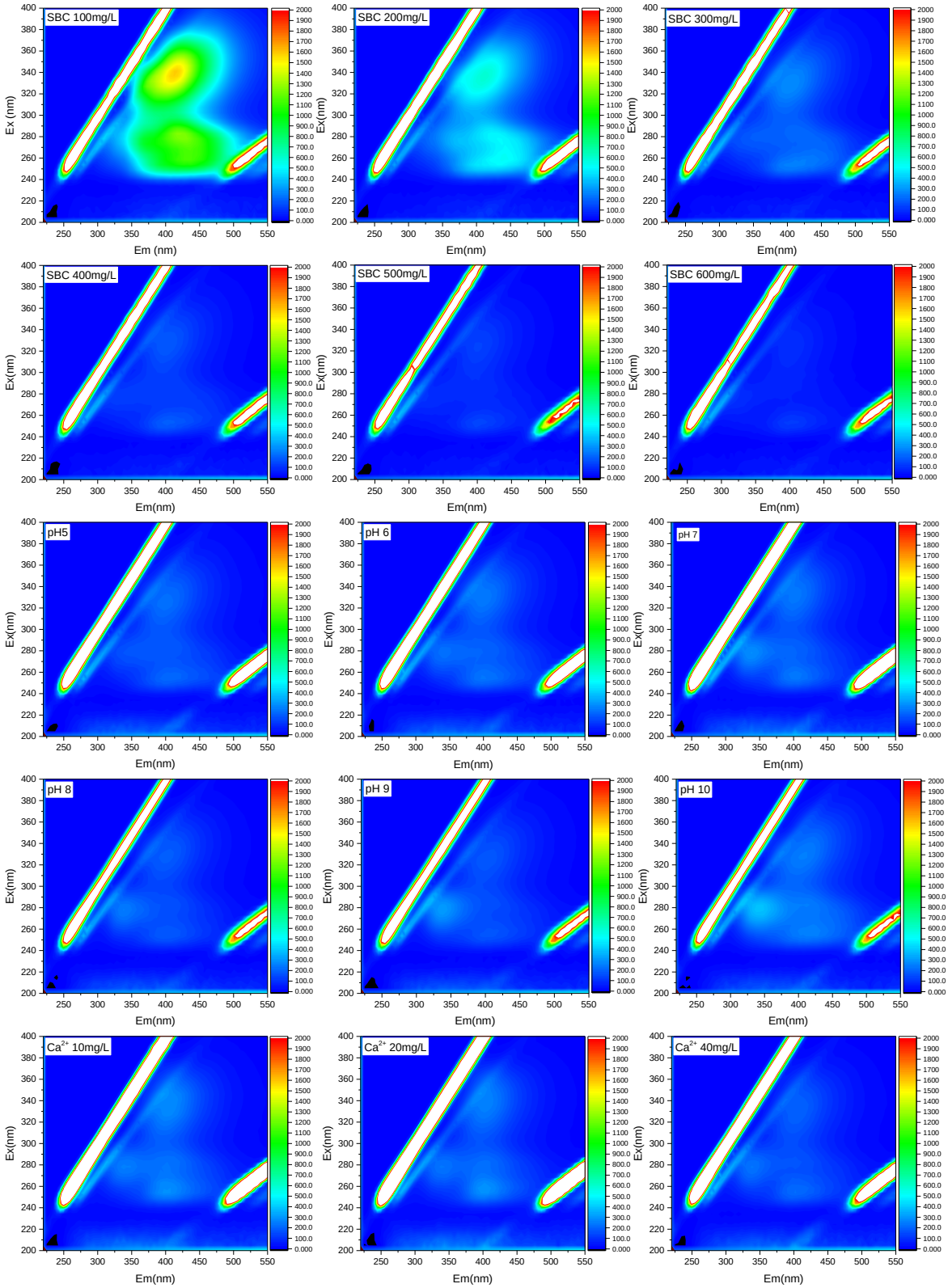

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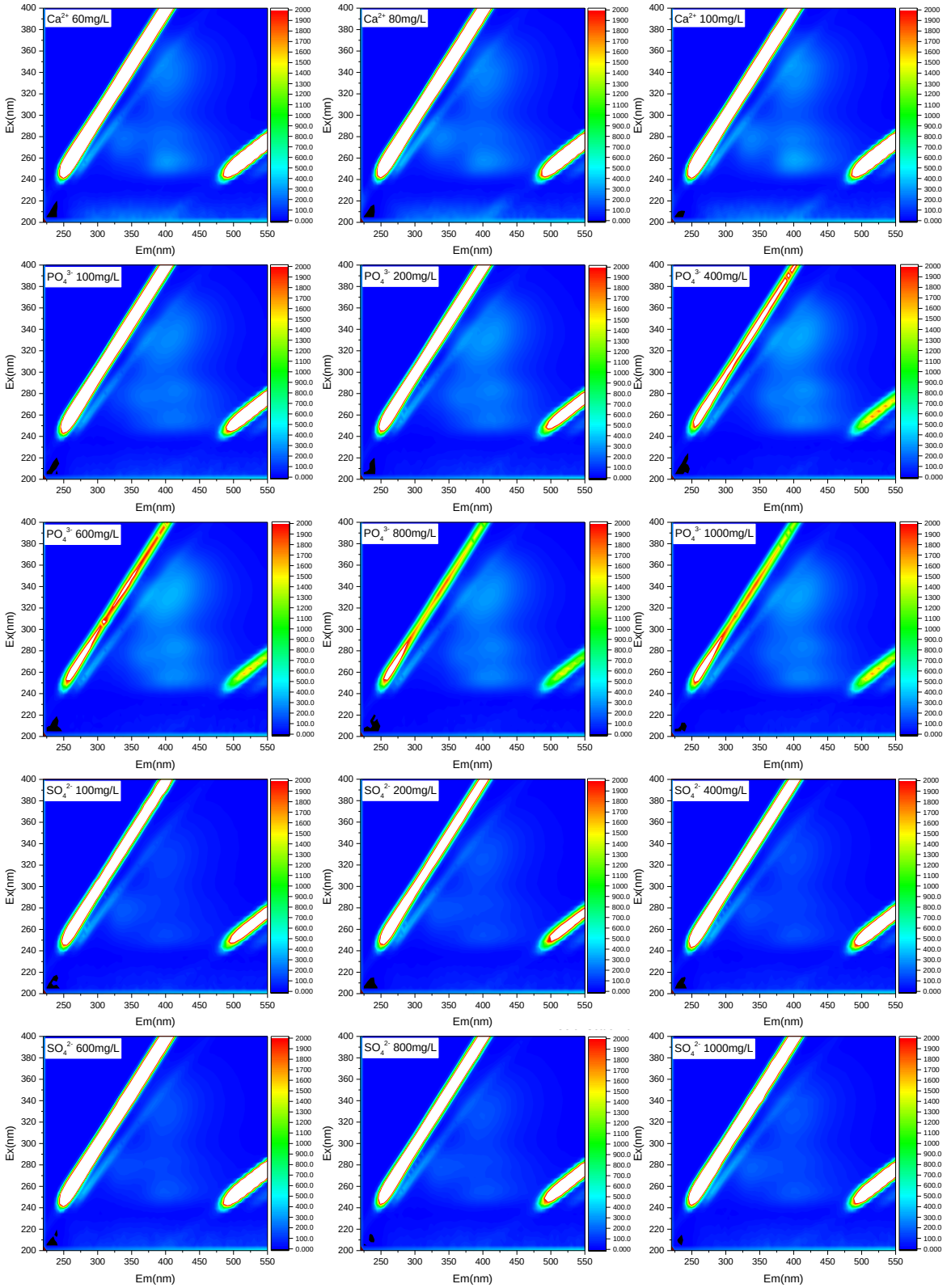

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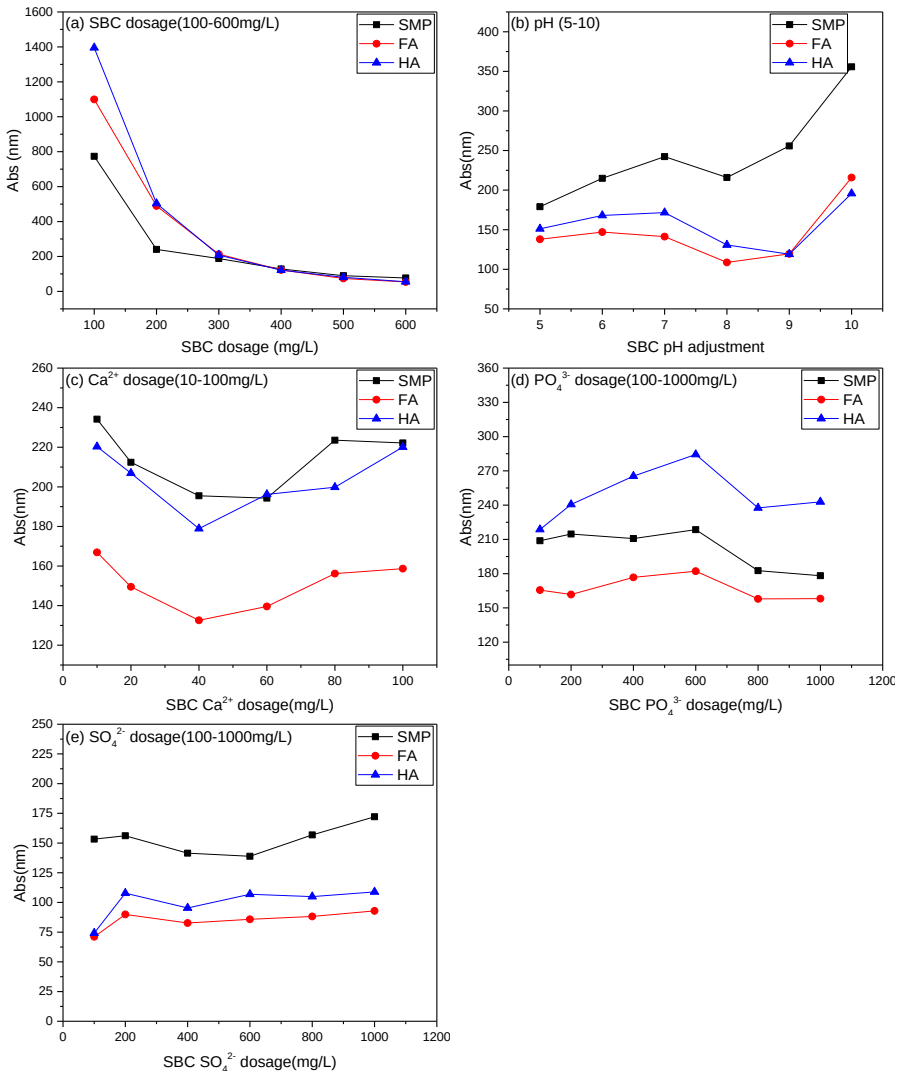

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