

RESEARCH ARTICLE

A Highly Sensitive and Simple Spectrophotometric Method for the Determination of Bisphenol F in Environmental Water Samples via Diazotization-Coupling Reaction

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ABSTRACT

In this work, a spectrophotometric method is proposed for Bisphenol F (BPF) tracking in environmental water system, which is based on targeted chemical derivatization. The practical aspects of the synthesis, diazotization and controlled coupling of sulfanilic acid to BPF in alkaline media to produce the highly stable dark-red azo chromophore were successfully completed. In the lab, optimal reaction conditions were determined and the reaction conditions were maintained at 50 °C for 50 minutes to obtain a peak absorbance λ_{max} at 431 nm. This binding ratio was confirmed by the stoichiometric testing. A high sensitivity (LOD: 0.0115 $\mu\text{g/mL}$) and an excellent linear working range (1.0-12.0 $\mu\text{g/mL}$ with an $R^2 = 0.997$) were found. The percentage recovery in the validation trial was determined to be very good (103.05%) and there was very little interference from the coeluting phenolics. This method was structurally applied to various natural systems, efficiently quantified trace BPF in wastewater, local rivers and lakes. However, for environmental water samples containing BPF at concentrations below the method's linear working range, a suitable preconcentration step may be required to achieve reliable trace-level determination.

Keywords: Bisphenol F, Spectrophotometry, Diazotization-coupling, Sulfanilic acid, Azo dye, Water samples.

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1. Introduction

In recent times, phenolic pollutants have gained considerable attention because of their ubiquitous occurrence in the aquatic environment, stemming from industrial and domestic effluents and from various chemical reactions and manufacturing processes [1, 2]. These compounds are relatively stable and have high water solubility, leading to migration and dispersion in surface and ground water, and a possible entry into the food chain and effect on aquatic organisms [3]. Many of these compounds are also highly toxic at low concentrations and some are endocrine disrupting compounds that can cause disruption of the growth, reproduction and ecological balance of aquatic organisms [4, 5]. Hence, monitoring and analytical of these compounds have become a necessity to understand and evaluate water quality and water environment protection [6, 7]. Bisphenol F (BPF) is regarded as an important phenolic derivative among these compounds, which has been used in the place of some conventional bisphenol as a substitute because it is structurally and chemically similar to these compounds. Compared with other bisphenol analogues, the increasing use of BPF as an alternative to conventional bisphenols and its potential occurrence in aquatic environments highlight the importance

of its specific monitoring in environmental water samples [8, 9]. This compound features two hydroxyl groups bound to two aromatic rings, thus allowing a high degree of chemical reactivity and a number of derivatization reactions that are used in industry and analysis [10, 11]. Furthermore, BPF has a relatively low molecular weight with a good thermal and chemical stability and can be used in polymer industries, production of epoxy resin, adhesives, protective coatings and some heatresistant plastics [12, 13]. It was also recently suggested that it might migrate from industrial products into aquatic and food environments, where its potential health and ecological effects [14], especially when exposed chronically, are of concern. Chemical stability and resistance to biodegradation make the elimination of BPF from water a major environmental problem, particularly if it is detected at low concentrations in water and is hard to remove using conventional water treatment processes [15, 16]. Various analytical procedures have been applied for the determination of phenolic compounds, including BPF, such as high performance liquid chromatography (HPLC), Gas chromatography–mass spectrometry (GC-MS) and electrochemical methods [17, 18]. But these methods are usually complicated to carry out, expensive, and can also be subject to matrix interferences [19, 20]. Therefore, considerable research has been conducted in recent years on the development of spectrophotometric methods involving chemical derivatization reactions leading to the coloration of complexes or derivatized products with a high UV–Visible absorbance value [21, 22]. These methods are simple, fast, highly sensitive and inexpensive when compared to conventional analytical methods [23, 24]. Diazotization and coupling reactions are among the most important reactions which are used in this field and result in the formation of colored azo compounds which have a characteristic visible region absorbance, this makes it possible to determine the phenolics accurately and efficiently [25, 26]. This reaction takes place in an acid solution, requires the formation of a diazonium salt, and involves coupling with an activated aromatic compound to produce a high color intensity, stable azo dye [27, 28]. Several factors such as type of medium, pH, reagent concentration and reaction time influence the reaction efficiency and therefore optimization of these parameters is needed to obtain maximum sensitivity and analytical accuracy [29, 30]. Although analytical techniques used for the detection of phenolics have come a long way, there is still a need for the development of more sensitive, selective and user-friendly analytical methods, particularly those that rely on direct spectrophotometric detection [31, 32]. Thus, the present study seeks a sensitive and simple spectrophotometric method for the determination of BPF in aqueous samples using diazotization coupling reaction, and to study the optimum reaction conditions to achieve the best spectrophotometric response and the minimum detection limits. Furthermore, study assesses the accuracy and reliability of the proposed method and its applicability on the environmental analysis.

2. Materials and methods

2.1. Instrumentation

The spectrophotometric measurements and absorbance readings for diazotization-coupling reaction were performed using double beam (UV-Vis) spectrophotometer (UV-1800, Shimadzu, Japan) in the wavelength range of (200 - 800) nm with (1 cm) quartz cell. The pH of the prepared solutions was checked and adjusted by using a calibrated pH metre. The thermostatic water bath (VELP Scientific, Europe) was used to control the sample temperature. All reagents and chemical substances were accurately weighed by using an analytical electronic balance (Kern and SOHN GmbH, China) having a sensitivity of ± 0.0001 g, during the experimental work.

2.2. Reagents and materials

The chemicals employed during the entire course of this study were of analytical reagent grade and were purchased from Merck and Sigma-Aldrich. The Bisphenol F (BPF) stock solution ($1000 \mu\text{g mL}^{-1}$) was prepared by accurately weighing 0.1 g of BPF, dissolving it in distilled water, and diluting to 100 mL in a volumetric flask. Working BPF solutions were prepared by appropriate dilution of the stock solution with distilled water to obtain the required concentrations within the linear range of $1\text{--}12 \mu\text{g mL}^{-1}$. The sulfanilic acid solution

(0.001 M) was prepared in distilled water and used as the primary reagent for diazonium ion formation. A freshly prepared 1% w/v sodium nitrite solution was prepared daily in distilled water before the diazotization step to maintain reagent stability and analytical accuracy. Hydrochloric acid (1 M) and sodium hydroxide (1 M) solutions were used as the optimum acidic and alkaline media for completing the diazotization–coupling reaction and developing the colored azo dye.

2.3. General analytical procedure

The optimized analytical procedure was used for the determination of Bisphenol F (BPF) by UV–Visible spectrophotometry based on the diazotization–coupling reaction. Briefly, 0.8 mL of sulfanilic acid solution (0.001 M) was pipetted into a 10 mL volumetric flask, followed by the addition of 0.4 mL of hydrochloric acid solution (1 M) and 0.5 mL of freshly prepared sodium nitrite solution (1% w/v). The mixture was cooled in an ice bath at 0–5 °C for 10 min to enhance the stability of the diazonium salt formed. Then, 1.0 mL of BPF working solution was added to obtain the desired concentration within the linear range of 1–12 $\mu\text{g mL}^{-1}$. Subsequently, 0.6 mL of sodium hydroxide solution (1 M) was added to provide the alkaline medium required for the coupling reaction and formation of the colored azo dye. The absorbance was measured against a reagent blank prepared under the same conditions but without BPF at the maximum absorption wavelength (λ_{max}) of 431 nm, and the solution was then diluted to the mark with distilled water.

3. Results and discussion

3.1. Absorption spectrum

The spectroscopic method adopted in both suggested methods is based on the coupling reaction of Sulfanilic with (BPF) in an alkaline solution when they form a color from which absorption spectrum can be measured. A spectroscopic scan was carried out in a control sample at this wavelength, to find the maximum absorption wavelength (λ_{max}) of the formed product. The increase in wavelengths will be in the direction of shorter wavelengths, which means that more color will be concentrated in the visible region, and this will be the azo dye. As illustrated in Figure (1), both methods showed high absorbance of the formed azo dye at (431) nm with high sensitivity and selectivity towards the estimation of BPF with a minimum interference effect of other reagents.

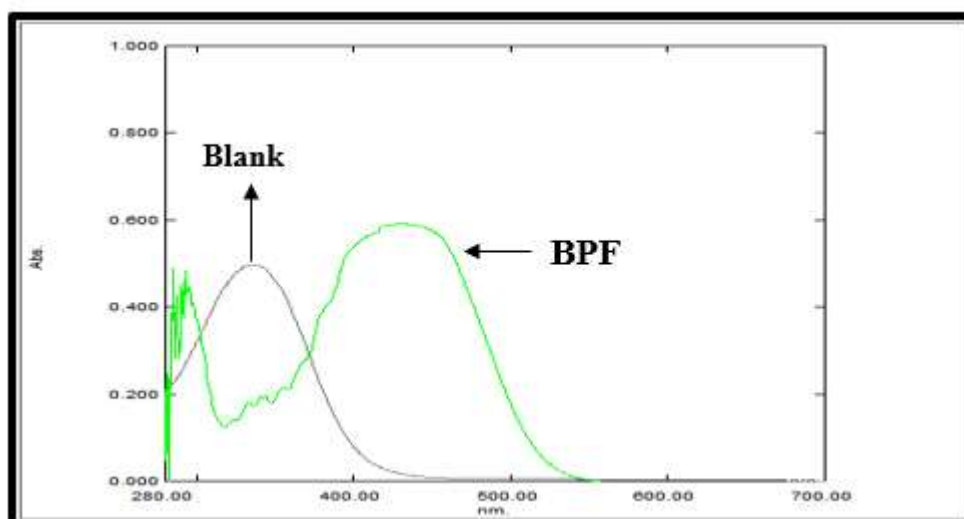
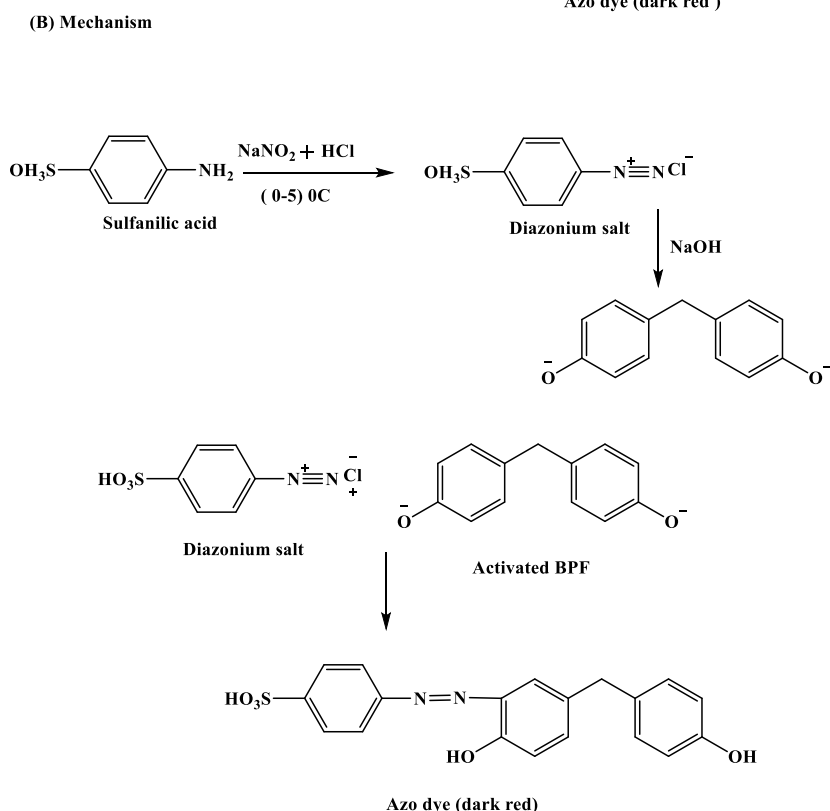
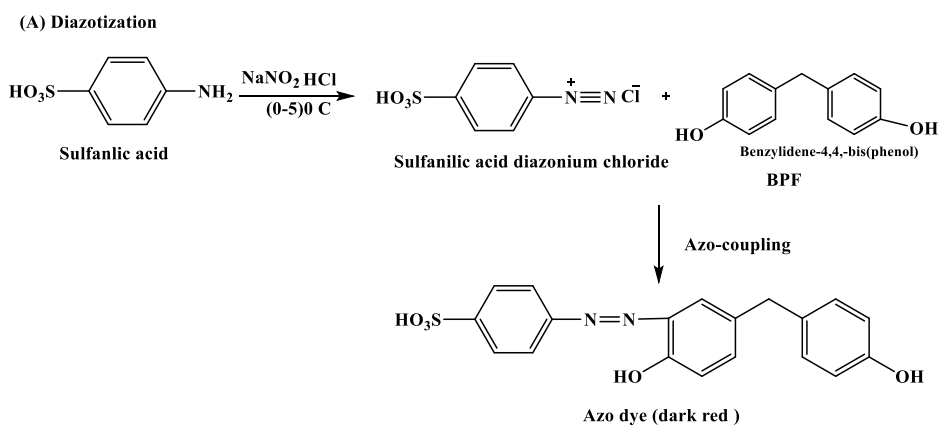


Figure 1. absorption Spectra of the form azo dye versus reagent blank, with λ_{max} appearing in 431

3.2. Proposed reaction mechanism

The proposed mechanism for the reaction was based on the chemical reactivity of the reacting compounds and the spectral properties of the products obtained as summarized in Scheme 1. The reaction takes place in

two steps: diazotization and azo-coupling. The diazotization step involved diazotization of sulfanilic acid containing the primary aromatic amino group, in hydrochloric acid (HCl) medium at low temperature (0–5 °C) with sodium nitrite (NaNO₂). In this case, nitrous acid (HNO₂) was produced in situ and then used in the reaction with the amino group of the sulfanilic acid to give the sulfanilic diazonium salt. It was important that the reaction mixture was maintained at low temperature to keep the diazonium ion stable, and to avoid its thermal decomposition before the coupling reaction. The following azo-coupling reaction was an electrophilic aromatic substitution reaction of the diazonium ion with Bisphenol F (BPF) in the alkaline medium. The resonance activation with the hydroxyl groups of BPF into the phenoxide ions in the presence of sodium hydroxide greatly enhanced the electron density of the aromatic rings. This made the aromatic nucleus very susceptible to electrophilic attack by the diazonium cation, and the activated ortho/para positions relative to the hydroxyl substituents were the preferred sites for azo coupling. The coupling reaction led to the formation of a stable dark-red azo dye with a long π -electron conjugated system, including the azo linkage (–N=N–) and the aromatic rings. This extensive electronic delocalization makes the chromophore produced exceptionally colored and with a high molar absorptivity, mostly because of the increased absorption in the visible range of the spectrum.



Scheme 1. Proposed reaction mechanism for the formation of the azo dye between diazotized Sulfanilic and bisphenol F (BPF)

3.3. Optimization of reaction conditions

3.3.1. Optimization of acid and base type

Different acids and bases were investigated to determine the optimum reaction medium for the formation of the azo dye. Among the tested acids, hydrochloric acid (HCl) produced the highest absorbance (0.298), compared with H₂SO₄ (0.217), H₃PO₄ (0.228), and CH₃COOH (0.261). The higher response obtained with HCl indicates that it provided a suitable acidic medium for the diazotization of sulfanilic acid and formation of a stable diazonium salt. Among the tested bases, NaOH gave the highest absorbance (0.352), followed by NaHCO₃ (0.346), KOH (0.341), and Ba(OH)₂ (0.321). The higher response with NaOH can be attributed to its ability to promote deprotonation of the hydroxyl groups of BPF, generating phenoxide ions and increasing the electron density of the aromatic rings, thereby enhancing the azo-coupling reaction. Therefore, HCl and NaOH were selected as the optimum acid and base for subsequent experiments.

Table 1. Optimization of acid, base and active surface types for the azo dye formation at (431) nm

Material Type		Absorbance at 431 nm
Acid	HCl	0.298
	H ₂ SO ₄	0.217
	H ₃ PO ₄	0.228
	CH ₃ COOH	0.261
Base	NaOH	0.352
	KOH	0.341
	Ba (OH) ₂	0.321
	NaHCO ₃	0.346

3.3.2. Optimization of acid and base volume

The volumes of 1 M HCl and 1 M NaOH were investigated over the range of 0.1–1.0 mL to determine their optimum volumes for azo dye formation. The absorbance increased with increasing HCl volume up to 0.4 mL, where the maximum absorbance of 0.352 was obtained. Further increase in the acid volume resulted in a gradual decrease in absorbance, indicating that excessive acidity was unfavorable for the subsequent coupling reaction. Therefore, 0.4 mL of 1 M HCl was selected as the optimum volume. For NaOH, the absorbance increased with increasing volume and reached a maximum value of 0.396 at 0.6 mL. Further addition of NaOH resulted in a decrease in absorbance. This behavior indicates that 0.6 mL provided a suitable alkaline medium for activation of BPF and efficient formation of the azo dye, whereas excessive alkalinity may adversely affect the stability of the coloured product. Accordingly, 0.4 mL of HCl and 0.6 mL of NaOH were selected for subsequent experiments.

Table 2. Optimization of acid and base volume for the azo dye formation at (431) nm

Volume of 1M acids	AbS of HCL at λ max =431	Abs of NaOH at λ max =431
0.1	0.306	0.321
0.2	0.316	0.365
0.3	0.324	0.373
0.4	0.352	0.384
0.5	0.344	0.390
0.6	0.331	0.396
0.7	0.326	0.390
0.8	0.318	0.382
0.9	0.307	0.371
1.0	0.298	0.353

3.3.3. Optimization of NaNO₂, urea, and the coupling reagent volumes

As can be observed from the data obtained in table (3), the volume of the reagents used in the formation of the azo dye has a significant effect on the absorption value. Any change in the proportion of these reagents would affect the efficiency of the reaction in the resulting colour intensity, with the optimal volume of sodium nitrite (NaNO₂) being (0.5) ml, which was explained as the amount of appropriate concentration of nitrous ions required to convert Sulfanilic to diazonium salt efficiently. Lower volumes of NaNO₂ may result in incomplete diazotization, whereas excess NaNO₂ increases the concentration of nitrous acid in the reaction medium, which may adversely affect the stability of the diazonium salt and the subsequent azo-coupling reaction. Therefore, 0.5 mL of NaNO₂ was selected as the optimum volume to ensure efficient diazotization while avoiding excess nitrite. On the other hand, adding (0.4) ml, of urea increased the absorption value to (0.502) nm, this is attributed to urea's role in removing nitrous acid (HNO₂) residues from the reaction medium, thus reducing the occurrence of secondary reactions that could affect dye formation or decrease its stability. The coupling reaction efficiency has, therefore, become more efficient, and the intensity of the color has increased. Regarding the coupling reagent, the highest absorption value of (0.524) ml was recorded with (0.8) ml of the reagent, this might be due to the favourable interaction ratio between the diazonium ion and the coupling organic compound which make the coupling with the activated aromatic ring in the azo compound to get the high absorption intensity with the coupling system. These results were used to select the following optimal conditions for the highest spectral response for the most sensitive estimation in (431) nm.

Table 3. Optimization of reagent volume for the azo dye formation at (431) nm

Volume of 1M acids	Abs of NaNO ₂	Abs of urea	Abs of reagent
0.1	0.403	0.428	0.408
0.2	0.408	0.452	0.416
0.3	0.410	0.438	0.442
0.4	0.414	0.502	0.461
0.5	0.416	0.493	0.487
0.6	0.412	0.481	0.493
0.7	0.406	0.462	0.515
0.8	0.403	0.431	0.524
0.9	0.408	0.422	0.511
1.0	0.410	0.416	0.501

3.3.4. Optimization of reaction time

The absorbance intensity of the reaction was found to be in relation to the reaction time as shown in Figure (2). This absorbance value was reached after (50) min and is the maximum value, this means that the production of the azo dye is not instantaneous but requires enough time for the diazonium ion of (BPF) to undergo the coupling reaction, and for the conjugated electron system to form the colour of the azo dye. It is believed that this behavior is due to the kinetically controlled azo coupling reaction. The reacting molecules must have a stable time to achieve the maximum level of reaction and create a stable azo bond (N=N), in the conjugated aromatic structure. In addition, the absorbance value at the specified wavelength gradually increases with the progress of the reaction, which indicates the stability of the dye product derived from the reaction. It is observed that the values of absorption gradually increase in the table with increase in heating time, for (BPF).

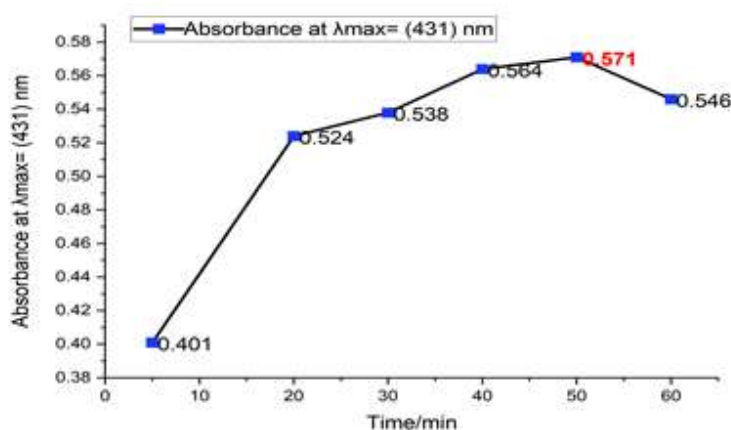


Figure 2. Effect of reaction time on absorption of the form azo dye at 431

3.3.5. Optimization of temperature

The obtained result in Figure (3) revealed that the intensity of the absorbance of the formed azo dye was at its peak at temperature 50 °C with absorbance value of 0.627 for the determination of BPF. The rise of absorbance with temperature might be due to the ability to supply the activation energy that is necessary for electrophilic azo coupling reactions between the diazonium salt and BPF, which increases dye formation and color development. The absorbance, however, decreased above 50 °C, this could be explained by the fact that the diazonium salt is thermally unstable, and thus was decomposed before the coupling reaction could be completed. Moreover, the excessive heating may cause partial decomposition of the formed azo dye or disruption of resonance stability of the azo linkage $-\text{N}=\text{N}-$. Hence, the optimum temperature of 50 °C was chosen because the spectrophotometric response was maximum which resulted in better sensitivity and analytical accuracy for the determination of BPF.

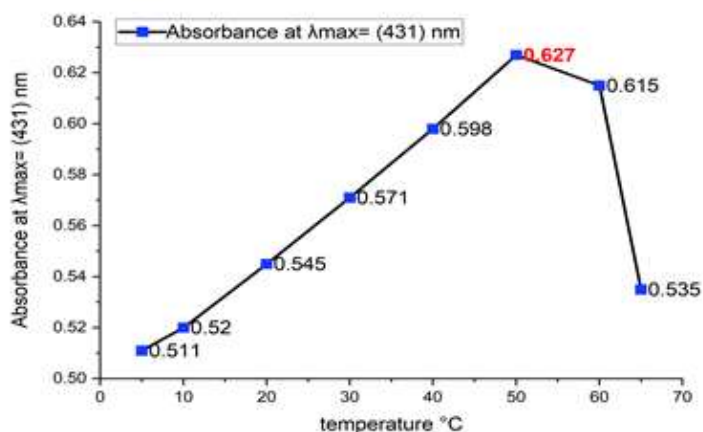


Figure 3. Effect of temperature on absorption of the form azo dye at 431

3.3.6. Optimization of solvent type

The effect of solvent type on the absorbance of the formed azo dye was investigated using different solvents under the optimized reaction conditions. As shown in Table 4, water produced the highest absorbance (0.572), followed by ethanol (0.533), methanol (0.520), acetonitrile (0.481), 1-propanol (0.467), and acetone

(0.450). The higher response obtained with water can be attributed to its high polarity and dielectric constant, which favor the stabilization of the ionic species involved in the diazotization–coupling reaction and facilitate the formation of the coloured azo dye. Therefore, the solvent type significantly affected the spectrophotometric response of the formed azo dye, with water providing the highest absorbance among the solvents investigated. Accordingly, water was selected as the optimum solvent for subsequent experiments.

Table 4. Effect of solvent on absorbance

Solvent	Absorbance at 431nm
Water	0.572
Ethanol	0.533
Methanol	0.520
Acetonitrile	0.481
1-Propanol	0.467
Acetone	0.450

3.3.7. Optimization of addition sequence

The effect of the order of reagent addition on the formation of the azo dye was investigated. As shown in Table 5, the highest absorbance (0.572) was obtained with the sequence A + B + C + D + E + F, whereas the alternative sequences produced lower absorbance values. The higher response obtained with the selected sequence indicates that the order of addition influences the efficiency of the diazotization–coupling reaction. The selected sequence provides suitable conditions for the formation of the diazonium species before the coupling step, followed by development of the coloured azo dye under alkaline conditions. Therefore, A + B + C + D + E + F was selected as the optimum addition sequence for the subsequent analytical measurements.

Table 5. Effect of addition sequence

Addition	Absorbance at 431 nm
A+B+C+D+E+F	0.572
A+F+E+C+D+B	0.431
A+E+B+C+D+F	0.375

A= Reagent, B= Acid, C= Sodium nitrite, D= Urea, E=Bisphenol (BPF), F= Base

3.4. Stoichiometric ratio (Job's method)

The results of the job method in figure (5) showed that the molar ratio of BPF to reagent is 1:1 and this ratio gave the maximum absorption value (0.443) nm. This is due to the efficiency of the electrophilic coupling reaction and the resonance stability of the product azo dye. The intensity of the peak also indicates the stability of the colored complex and the lack of side reactions, which validates the choice of operating conditions. Hence, this ratio is a good foundation for the sensitive quantitative estimation of the compound in water.

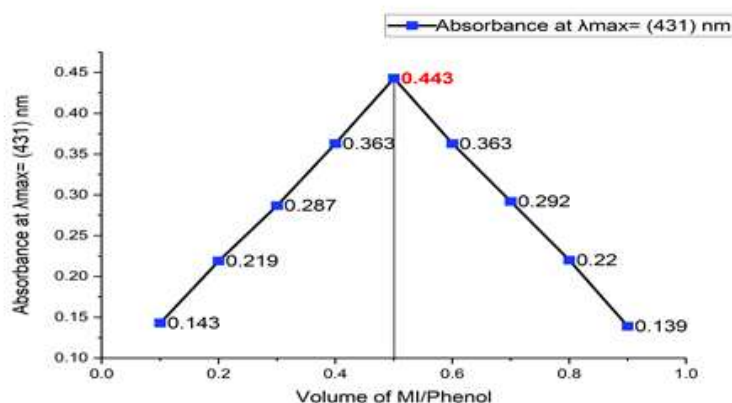


Figure 5. Determination of the Stoichiometric ratio of the azo dye using the continuous variation method

3.5. Stoichiometric ratio (Mole ratio method)

Optimal conditions for spectrophotometric determination of BPF were found to be 50 min reaction time and 50 °C, under which the colour intensity of the azo dye formed was maximum and the azo dye was most stable. Water was chosen as the solvent because of its high polarity and its stabilizing effect on the ionic species in the chromophoric system. Efficient diazotization was achieved with the chosen sequence of reagent addition, with minimal possibility of side reactions. The molar ratio study was conducted and it confirmed the 1:1 complexation of the azo dye and the diazotized reagent. An increase in absorbance at higher temperatures or longer reaction times was believed to be due to the thermal decomposition of the diazonium salt or instability of the azo dye. Such optimized conditions resulted in high analytical sensitivity, accuracy and reproducibility for the determination of BPF.

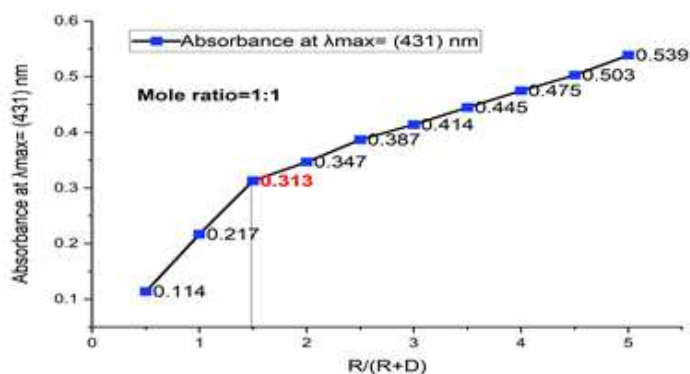


Figure 6. Determination of the Stoichiometric for the complex via mole ratio method

3.6. stability constant of the formed azo dye

The stability constant results showed that the azo dye obtained had good stability and it increased as the volume of BPF solution increased indicating the efficiency of the azo coupling reaction. Average stability constant values are used to indicate the suitability of the dye for sensitive spectroscopic and analytical applications, attributed to the activation of the aromatic ring by the hydroxyl groups (OH⁻), which gives enhanced stability of the dye through the involvement of electron resonance.

Table 6. Stability constant of the formed azo dye

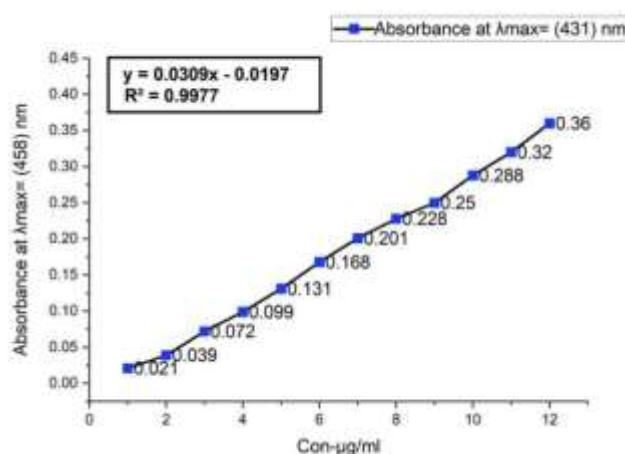
Parameter	Value
Stoichiometric ratio	1:1
Mean stability constant	4.3×10^3

3.7. Analytical performance and calibration curve

The calibration curve for BPF (Figure 7) showed a good linear relationship over the concentration range of 1–12 $\mu\text{g mL}^{-1}$, with a correlation coefficient (R^2) of 0.997, demonstrating the applicability of Beer–Lambert’s law at 431 nm. The molar absorptivity (ϵ) of the formed azo dye was calculated from the slope of the calibration curve according to the Beer–Lambert law ($A = \epsilon bc$). The slope of the calibration curve was 0.0309 $\text{mL } \mu\text{g}^{-1}$. Considering the molecular weight of BPF (200.23 g mol^{-1}), 1 $\mu\text{g mL}^{-1}$ corresponds to $4.9943 \times 10^{-6} \text{ mol L}^{-1}$. Therefore, at a path length of 1 cm, the molar absorptivity was calculated as follows:

$$\epsilon = 0.0309 / (4.9943 \times 10^{-6} \times 1) = 6187.107 \text{ L mol}^{-1} \text{ cm}^{-1}.$$

The Sandell’s sensitivity was 0.03236 $\mu\text{g cm}^{-2}$, indicating the applicability of the proposed spectrophotometric method for the determination of trace amounts of BPF.

**Figure 7.** Calibration curve (BPF)

3.8. Effect of interferences

The results in table (7) show that BPF exhibited the highest absorbance of (0.342) at (431) nm, compared to the other interfering compounds, confirming that that's good selectivity for this compound. The aniline and para nitrophenyl showed (0.329) and (0.318) absorbance value respectively, while 2nitrophenyl showed (0.253) and benzoic acid showed (0.122). In this variation, different efficiencies of these compounds to inform the chromophore lead to the different variations. So, the method was able to show that interfering substances do not significantly affect the estimation of (BPF) and that the method can be used for different analytical samples without any loss of accuracy.

Table 7. The effect of interferences on the absorbance BPF

NO.	Interference	Abs.
1	Aniline	0.329
2	Benzoic acid	0.122
3	2-nitrophenol	0.253
4	p-nitrophenol	0.318
5	Without	0.342

3.9. Analytical and statistical validation

The direct spectrophotometric method had a high efficiency and good linear range of 1–12 $\mu\text{g mL}^{-1}$ for the determination of BPF at the wavelength 431 nm with a correlation coefficient (R^2) of 0.997. The detection limit (LOD) and quantification limit (LOQ) of the method were 0.0115 and 0.0202 $\mu\text{g mL}^{-1}$, respectively, with a molar absorptivity of 6187.1070 $\text{L mol}^{-1} \text{cm}^{-1}$, which was satisfactory for the efficient formation of azo dyes. The proposed method also had a satisfactory recovery value of 103.0508% and the standard deviation value was 0.83% which is very good for the spectrophotometric determination of BPF in environmental samples and is very accurate, precise and reliable.

Table 8. Analytical and statistical performance of the proposed Method

Parameter	Value DCR
λ_{max}	431 nm
Linear range	1-12
Regression equation	$y=0.0309x-0.0197$
Correlation coefficient (r)	0.997
Limit of Detection (LOD)	0.0115
Limit of Quantification (LOQ)	0.0202
Molar absorptivity	6187.1070
Sandell's sensitivity	0.03236
Recovery (%)	103.0508
RSD (%)	0.83
C.L. at 12 $\mu\text{g mL}^{-1}$	12.1132 $\pm$ 0.1605743
C.L. at 9 $\mu\text{g mL}^{-1}$	9.1248 $\pm$ 0.0086626
C.L. at 6 $\mu\text{g mL}^{-1}$	6.1513 $\pm$ 0.0074808
C.L. at 3 $\mu\text{g mL}^{-1}$	3.2144 $\pm$ 0.00517681

3.10. Application to environmental water samples

The diazotization method proved to be an efficient method for the determination of BPF in environmental samples with recovery values of 100.21% to 102.27%. The relative error values had relatively low values (between 0.37% and 2.28%) and the RSD% values ranged from 0.0005% to 0.122%, which means that the precision and repeatability of the proposed method were very good. The results obtained show that the diazotization spectrophotometric method is accurate, reliable and suitable in the determination of BPF in various aqueous media.

Table 9. Application of the proposed method to environmental water samples for the Diazotization method

West water source	Amount added ($\mu\text{g mL}^{-1}$)	Amount found ($\mu\text{g mL}^{-1}$)	Recovery%	Average Recovery %	$E_{\text{rel}}\%$	Average $E_{\text{rel}}\%$	RSD%
Diyala river	20	20.2988	101.49	101.89	1.49	1.89	0.0018
	10	10.2278	102.27		2.28		0.0069
Khresan river	20	20.1658	100.82	101.22	0.83	0.72	0.122
	10	10.0618	101.61		0.62		0.0099
Lake Hamrin	20	20.0428	100.21	100.29	0.44	0.41	0.0005
	10	10.0370	100.37		0.37		0.0047

3.11. Comparative evaluation of the proposed method with reported analytical procedures

The analytical performance of the proposed spectrophotometric method was compared with previously reported methods for the determination of bisphenol F (BPF), as summarized in Table 10. Habib et al. (2023) developed a spectrophotometric method based on a diazotization-coupling reaction using diazotized metoclopramide, with a linear range of 0.5–10 $\mu\text{g mL}^{-1}$ and a detection limit of 0.15 $\mu\text{g mL}^{-1}$. The method was

applied to bottled water and thermal paper samples. In comparison, the present method employs diazotized sulfanilic acid and provides a wider linear range of 1–12 $\mu\text{g mL}^{-1}$ and a lower detection limit of 0.0115 $\mu\text{g mL}^{-1}$. Han et al. (2023) reported a high-performance liquid chromatography-ultraviolet (HPLC-UV) method for the simultaneous determination of 14 bisphenol pollutants, including BPF, in building materials. The reported method achieved complete separation within 40 min, with detection limits ranging from 0.002 to 0.040 mg L^{-1} and precision below 4.9%. Although the chromatographic method provides simultaneous determination of multiple bisphenols, the proposed UV-Vis method is simpler and requires less sophisticated instrumentation, while providing satisfactory sensitivity for BPF determination in environmental water samples. The comparison demonstrates that the proposed method provides a simple, rapid and cost-effective alternative for the determination of BPF, particularly when routine analysis of environmental water samples is required.

Table 10. Comparative of the proposed method with reported analytical methods

Analytical parameter	Present method	[10]	[33]
Analyte	BPF	BPF	14 bisphenols, including BPF
Analytical technique	UV-Vis spectrophotometry (diazotization-coupling)	UV-Vis spectrophotometry (diazotization-coupling)	HPLC-UV
λ_{max} / Detection	431 nm	461 nm	UV detection
Linear range	1–12 $\mu\text{g mL}^{-1}$	0.5–10 $\mu\text{g mL}^{-1}$	—
LOD	0.0115 $\mu\text{g mL}^{-1}$	0.15 $\mu\text{g mL}^{-1}$	0.002–0.040 mg L^{-1}
LOQ	0.0202 $\mu\text{g mL}^{-1}$	0.52 $\mu\text{g mL}^{-1}$	—
Recovery (%)	To be revised after validation	97.95–101.50	—
Sample/application	Environmental water samples	Bottled water and thermal paper	Building materials
Analysis characteristics	Simple, low-cost and direct spectrophotometric determination	Simple and low-cost spectrophotometric determination	Simultaneous chromatographic determination of multiple bisphenols

4. Conclusions

This study aimed to develop an efficient spectrophotometric method for determination of BPF in environmental samples by diazotization coupling technique by Sulfanilic reagent. The proposed method showed that the azo dye obtained was stable and had a maximum absorbance at 431 nm and good linearity in the studied range with a correlation coefficient value of 0.997. The results obtained also demonstrated good sensitivities and recovery percentages with high accuracy when the method was applied to various environmental water samples. Besides, the method is easy to operate, low analysis cost, and has good repeatability, which can be used for routine environmental monitoring of BPF.

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