Appraising the Spectral Interference of Dysprosium on 27 Analytes Using Capacitively Coupled Device Detector-based Inductively Coupled Plasma Atomic Emission Spectrometry Without Physical/Chemical Separation

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INTRODUCTION

The qualities and functions of lanthanides have long been the focus of research. Since lanthanides possess similar chemical and physical properties, they are difficult to separate. Due to their various uses in industry, they find application in many important and fundamental areas such as the functional materials in agriculture, as catalysts, and for other products. They easily enter into the environment and accumulate in organisms and finally become part of the food chain (1-4). The distinctive nature of unpaired 4f electrons causes the rare earth elements (REEs) to possess particular physical and chemical properties. Among the lanthanides, dysprosium (Dy) possesses high magnetic momentum (around 10.65 μ_B) and is used in various fields such as magnetic and magneto-optical recording with a large magnetostriction, magneto-caloric, etc. (5-9). The oxide of Dy, Dy₂O₃, is highly insoluble and thermally stable, suitable for glass, optical, and ceramic applications. (10).

In this study, a capacitively coupled device (CCD) as the detector in inductively coupled plasma atomic emission spectrometry (ICP-AES) analysis was used which records the spectrum over a large wavelength range owing to the coupling of a solid state array detector with an Echelle spectrograph. This wide coverage has the

ABSTRACT

In this work, a capacitively coupled device-based inductively coupled plasma atomic emission spectrometry method was used to determine the spectral interference of electron-rich elements for assessing some common analytes (Ag, Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Ga, In, Li, Mg, Mn, Na, Ni, Sr, Pb, Tl, and Zn) and some rare earth elements (Ce, Gd, La, Lu, Nd, and Pr) in a dysprosium matrix. The foremost lines for each of these elements were chosen after checking the analytical performance such as sensitivity, detection limit, linear dynamic range and precision, tolerance level, and correction factor due to the spectral interference of the electron-rich dysprosium (Dy). This methodology was verified by using synthetic samples and comparing the results with other reliable methods. The proposed method is efficient, simple, and less time-consuming for the determination of analytes in a Dy matrix without requiring physical/chemical separation.

special benefit of performing simultaneous multi-element detection and obtains spectral-free lines for each element as required for qualitative analysis (11). The CCD detector provides better resolution so that the spectral-free lines of the trace elements and the REEs can be determined.

The ICP-AES method provides high sensitivity, a large dynamic

range, reproducibility, and exceptional stability from matrix effects for the determination of trace amounts of REEs in geological and related materials (12-17). Matrix effects are mainly due to the high concentration range of REEs beyond their instrumental detection limits which then poses a problem in the determination of REEs present in low concentrations in many common substances (18). Most of the matrix elements falsify REE analytical results because of spectral overlaps and background continuum interferences. This problem could not be resolved with previous methods routinely used before ICP-OES, such as neutron activation analysis (NAA), X-ray fluorescence (XRF), and mass spectroscopy, etc. (19-22).

In our previous studies, the spectral interference of U, Th, Zr, Gd, Lu, and Nd on different analytes and its implication in trace metallic impurity analysis (23-30) was investigated. In the present work, Dy was chosen as the emission-rich matrix and its spectral interference on common analytes, including specified rare earth elements.

EXPERIMENTAL

Instrumental Operating Conditions

The analysis was carried out using a Model Arcos FHS12 ICP-AES (Arcos, Germany), equipped with a high temperature argon plasma as a source of excitation and CCD as the detector system. The instrumental operating conditions and specifications are listed in Table I. The

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detector system, consisting of linear arrays of CCD detectors (3648 pixels/array) and thermally stabilized, provides the ability to select alternate analytical lines.

Standard Solutions and Reagents

Standard solutions for all of the elements were prepared from Certipur® ICP standard reference material solutions (E-Merck, Darmstadt, Germany) by proper dilution. Suprapur® HNO₃ (E-Merck, Darmstadt, Germany) and quartz double-distilled water were used throughout the study. Even though ICP-AES offers a high degree of linear dynamic range, for more precise calibration curves multi-point standardization was carried out using 0.5 M HNO₃ as a lower standard and 0.05–500 mg/L of the corres-

ponding elemental standard as the higher standard for each line after proper peak search, auto-attenuation, etc. For the analysis of each sample, 10 replicate measurements were carried out, while for determination of the detection limits and sensitivity, 25 replicate measurements were taken into account.

Methods

The method chosen for studying the spectral interference and selecting the best line(s) in the presence of Dy, each analyte was studied by preparing a series of Dy solutions (standard reference material elemental solution from E-Merck, Darmstadt, Germany) of varying concentrations from 0.05 mg/L to 500 mg/L. The contribution due to Dy in each different channel of each of the analytes was observed

and the correction factor, tolerance level, as well as the analytical performance, such as detection limit, sensitivity, linear dynamic range, and precision for each analyte, were evaluated. Considering that the correction factor depends on the concentration of the interfering element (Dy), ICP-AES is the method of choice to directly determine the interferent in the presence of other analytes. The analytical performance for each identified line of Dy was evaluated. The tolerance level is the maximum concentration of the interfering element up to which point there is no spectral interference on the particular emission line of the analyte.

Background correction was performed by the two-point method off-line after the experiments were carried out. In the two-point calibration, two points have to be chosen on both sides of the peak. The software of the instrument then creates a straight line considering these two points. This straight line is considered the background for the peak corresponding to the analytical line.

The developed methodology for the direct determination of trace amounts of 27 analytes (Ag, Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Ga, In, Li, Mg, Mn, Na, Ni, Sr, Pb, Tl, and Zn) and some rare earth elements (Ce, Gd, La, Lu, Nd, and Pr) was performed using synthetic samples without chemical separation. The method was compared with other techniques for determining trace amount of common analytes, except for Ag, which is being added to the sample in the form of AgCl. The D.C. arc carrier distillation technique was used, while for the rare earth elements ion chromatography was used for comparison purposes. The results obtained from this newly developed method were compared with flame atomic absorption spectrometry (FAAS) analysis.

TABLE I
Specifications and Instrumental Operating Conditions of ICP-AES

Instrumental Specifications	
Optical design	Arcos FHS12 ICP-AES
Paschen-Runge mounting	Circular design
Focal length	750 mm
Grating	Holographic
Groove density	1800 grooves/mm (1), 3600 grooves/mm (2)
Wavelength range	130-800 nm
Entrance slit width	15 microns
Resolution (FWHM)	0.01 nm from 130-450 nm 0.02 nm from 450-800 nm
Thermal regulation	Controlled to 30 ± 1 °C
Frequency	27.12 MHz
Pump	Dual channel peristaltic pump
Detector	Linear arrays of CCD (3648 pixels/array)
Nebulizer	Cross flow
ICP-torch	Demountable, radial viewing
Operating Conditions	
Coolant flow	16 L/min
Auxiliary flow	0.5 L/min
Total time of measurement	26 s
Pump speed	28 rpm
RF power output	1.1 kW
Input power	230 V AC

RESULTS AND DISCUSSION

Simultaneous Determination of Dy by ICP-AES

Since the contribution of Dy on different analytes is dependent on its concentration, it is required that the correct amount present in the sample is determined. Also, for defining the spectral interference quantitatively, the correction factor (which is a function of the concentration of the interfering element) of each identified line must be known. An ICP-AES method was developed for the determination of Dy along with the analytes. Even though Dy has a line-rich emission spectra, only five lines were chosen on the basis of the analytical performance. The calibration curves for the five chosen lines of Dy (340.780 nm, 353.170 nm, 353.602 nm, 364.540 nm, and 394.468 nm) were established as shown in Figure 1. The detection limit of Dy using these lines follows the trend: 353.170 nm < 364.540 nm < 340.780 nm < 394.468 nm < 353.602 nm, while that of sensitivity follows the trend: 353.170 nm > 364.540 nm > 340.780 nm ~ 353.602 nm > 394.468 nm, respectively. The slope of the calibration curves was considered as the sensitivity of the analytical lines, whereas the detection limits were calculated as the concentration equivalent to the intensity of the blank (< x >) + 5 times of the rela-

tive standard deviation values of the blank (5σ). Synthetic samples containing Dy in the concentration range of 0.05 mg/L – 500 mg/L were analyzed using these analytical lines to validate the method for the determination of Dy. The analytical results are summarized in Table II.

Spectral Interference of Dy on Other Analytes

Dysprosium is an important member of the lanthanide series and has [Xe] $4f^{10}$, $6s^2$ ground state electronic configuration and 5I_8 ground state term. The spectral study of Dy revealed various transition lines in the spectrum due to its multi-electronic nature and, there-

fore, it interfered in the determination of other analytes. The study of spectral interference along with the analytical performance for each analyte is shown in Tables III–VIII. The best lines for each analyte were chosen on the basis of spectral interference and analytical performance (detection limit, sensitivity, linear dynamic range, and precision).

Effect on Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg

These analytes are selectively grouped because they have some spectral-free line(s) as shown in Table III, and their analytical performance is listed in Table IV.

Fig. 1. Calibration Curves for Different Analytical Lines of Dy.

TABLE II
Determination of Dy by ICP-AES

Dy (mg/L)	340.78 nm (mg/L)	353.17 nm (mg/L)	353.602 nm (mg/L)	364.54 nm (mg/L)	394.468 nm (mg/L)
1	0.97 ± 0.04	1.07 ± 0.05	1.02 ± 0.06	0.99 ± 0.04	0.98 ± 0.04
10	10.4 ± 0.5	9.7 ± 0.5	9.5 ± 0.5	10.2 ± 0.4	9.6 ± 0.4
50	51 ± 2	47 ± 3	49 ± 3	50 ± 3	50 ± 5
100	96 ± 5	101 ± 3	104 ± 5	97 ± 3	98 ± 4
500	489 ± 10	497 ± 8	508 ± 9	503 ± 5	500 ± 6
D.L. (mg/L)	0.046	0.006	0.065	0.032	0.05
Sensitivity (counts/mg/L)	4.2 x 10 ³	17 x 10 ³	4.4 x 10 ³	4.7 x 10 ³	4.1 x 10 ³
Linear Dynamic Range (mg/L)	0.046–1000	0.006–1000	0.065–1000	0.032–1000	0.050–1000

Cadmium (Cd)

Cadmium has one spectral-free line, 226.502 nm, among its four chosen lines. The sensitivity for the four lines follows the order: 226.502 nm > 214.438 nm > 228.802 nm > 361.051 nm. Thus, the Cd 226.502-nm line is chosen for further quantitative analysis.

Lithium (Li)

The only line which seems best for Li, based on both the analytical performance and spectral interference, is 670.780 nm and was chosen for further studies.

Manganese (Mn)

Though the analytical performance results for the five lines of Mn (257.611 nm, 259.373 nm, 260.569 nm, 294.921 nm, and 403.076 nm) are found to be similar, the spectral interference result reveals that the only line of Mn that is not interfered is 259.373 nm and hence, was chosen for further studies in a Dy matrix.

Strontium (Sr)

Among the three lines of Sr (407.771 nm, 421.552 nm, and 460.733 nm), the former two lines show similar analytical performance (includes detection limit, sensitivity, linear dynamic range, %RSD). However, the 421.552-nm line was found not to be interfered in a Dy matrix, while the 407.771-nm line does. Thus, the 421.552-nm line was selectively chosen for the quantitative studies of Sr in a Dy matrix.

Praseodmium (Pr)

The sensitivity of all four lines of Pr (411.846 nm, 417.939 nm, 422.535 nm, and 414.311 nm) were found to be similar. The only line that is not interfered by Dy is 417.939 nm and thus was chosen as the best line for use in further studies.

Sodium (Na)

The two lines (588.995 nm and 589.592 nm) of Na were found to

have similar analytical performance results and are not interfered in a Dy matrix. Thus, these two lines are best for the quantitative study of Na in a Dy matrix.

Zinc (Zn)

The detection limit trend for the four lines of Zn is as follows: 213.856 nm < 202.613 nm < 206.200 nm < 334.502 nm. It was found that the 213.856-nm line is the only line of Zn which is not interfered in a Dy matrix. Thus, the 213.856-nm line of Zn is best for further studies in a Dy matrix.

Lanthanum (La)

All three lines of La (333.749 nm, 379.478 nm, and 408.672 nm) show similar detection limit, but the 333.749-nm line is interfered. Thus, the 379.478-nm and 408.672-nm lines were chosen for quantitative study of La in a Dy matrix.

Lutetium (Lu)

From both the analytical performance and spectral interference point of view, the 261.542-nm line of Lu was found best for the estimation of Lu in a Dy matrix.

Magnesium (Mg)

The detection limit trend for the five lines of Mg is: 279.553 nm < 280.270 nm < 285.213 nm < 202.647 nm < 279.079 nm, respectively, while the sensitivity trend is just the reverse. The only line not interfered by Dy is 279.553 nm and hence, was chosen the best analytical line of Mg in a Dy matrix.

Effect on Ca, Fe, Co, Cu, Tl, Ag, B, and Cr

These eight analytes are selectively grouped because there are some line(s) of each analyte which are slightly interfered in a Dy matrix (see Table V). After incorporating the correction factor, it is possible to determine these analytes in a Dy matrix. The analytical performance result of these analytes is shown in Table VI.

Calcium (Ca)

The detection limit trend of the six chosen lines of Ca is: 393.366 nm < 396.847 nm < 422.673 nm < 317.933 nm < 315.887 nm < 183.801 nm. The sensitivity follows the reverse trend of the detection limit. The 393.366-nm line was found to interfere the least and was therefore chosen for studying Ca in a Dy matrix.

Iron (Fe)

Among the 10 analytical lines of Fe, the 239.562-nm line was found to interfere the least and had the best analytical performance results. Hence, this line was chosen for the quantitative determination of Fe in a Dy matrix.

Cobalt (Co)

The contribution of the four lines of Co in a Dy matrix follows the trend: 237.862 nm < 238.892 nm < 228.616 nm < 230.786 nm, respectively. The 237.862-nm line has the lowest detection limit in comparison to the other lines. Thus, it was selected as the best analytical line for Co in a Dy matrix.

Copper (Cu)

The contribution of the five lines of Cu in a Dy matrix follows the trend: 324.754 nm < 327.396 nm < 224.700 nm < 219.958 nm < 219.226 nm, respectively. The 324.754-nm line was found to have lower detection limit and higher sensitivity in comparison to the other lines. Hence, it was selected for Cu determination in a Dy matrix.

Thallium (Tl)

Among the two lines of Tl (190.864 nm and 276.787 nm), the only line worth noticing is 190.864 nm. This line has better analytical performance and spectral interference results than the 276.787 nm line and thus, was chosen best for studying Tl in a Dy matrix.

TABLE III
Spectral Interference of Dy on Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg

Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)	Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)
Cd	214.438	0.07	1.4×10^{-4}	200	Na	589.592	*	-	0.5
	226.502	*	-	500		588.995	*	-	0.5
	228.802	0.71	1.4×10^{-3}	5		330.237	#	-	1
	361.051	9.61	1.9×10^{-2}	10		330.298	#	-	5
Li	670.78	*	-	500	Zn	213.856	*	-	0.5
	460.289	1.31	2.6×10^{-3}	200		206.200	1.90	3.8×10^{-3}	5
	323.261	#	-	0.05		202.613	0.23	4.5×10^{-4}	0.5
	274.118	8.0	1.6×10^{-2}	50		334.502	14.0	2.8×10^{-2}	5
Mn	257.611	0.17	3.4×10^{-4}	200	La	408.672	*	-	500
	259.373	*	-	200		333.749	2.03	4.1×10^{-3}	10
	260.569	0.09	1.8×10^{-4}	200		379.478	*	-	500
	294.921	1.62	3.2×10^{-3}	5	Lu	261.542	*	2.0×10^{-4}	500
Sr	403.076	0.10	2.0×10^{-4}	200		291.139	0.68	1.3×10^{-3}	50
	407.771	0.58	1.2×10^{-3}	50		307.760	0.36	7.1×10^{-4}	200
	421.552	*	-	500		219.554	0.36	7.2×10^{-4}	50
Pr	460.733	0.31	6.1×10^{-4}	50	Mg	279.553	*	-	0.5
	411.846	0.48	9.6×10^{-4}	200		280.270	0.08	1.5×10^{-4}	0.5
	417.939	*	-	500		285.213	0.10	2.0×10^{-4}	50
	422.535	1.37	2.7×10^{-3}	10		279.079	3.50	7.0×10^{-3}	1
	414.311	#	-	0.05		202.647	0.69	1.4×10^{-3}	0.05

*No interference.

#significant spectral interference.

TABLE IV
Analytical Performance of Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg in Dy Matrix

Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	RSD (%)	Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynaic Range (mg/L)	RSD (%)
Cd	214.438	0.007	4084	0.007-1000	2	Na	330.237	1.97	61	1.91-800	4
	226.502	0.007	8972	0.007-1000	2		330.298	2.37	36	2.37-800	4
	228.802	0.04	1354	0.04-800	5		588.995	0.03	47676	0.03-1000	1
	361.051	0.51	331	0.51-500	5		589.592	0.01	27818	0.01-1000	1
Li	274.118	1.52	34	1.52-500	5	Zn	202.613	0.03	1649	0.03-1000	2
	323.261	0.22	147	0.22-900	4		206.200	0.2	144	0.2-900	2
	460.289	0.53	176	0.53-1000	2		213.856	0.002	14112	0.002-1000	1
	670.78	0.002	175101	0.002-1000	1		334.502	0.44	379	0.44-850	1
Mn	257.611	0.003	9189	0.003-1000	1	La	333.749	0.04	4104	0.04-1000	1
	259.373	0.003	8067	0.003-1000	1		379.478	0.04	6022	0.04-1000	1
	260.569	0.001	4193	0.001-1000	1		408.672	0.03	7071	0.03-1000	1
	294.921	0.05	1454	0.05-950	2	Lu	219.554	0.02	986	0.02-900	2
Sr	403.076	0.02	8572	0.02-975	2		261.542	0.004	7184	0.004-1000	2
	407.771	0.0005	369965	0.0005-1000	1		291.139	0.03	2955	0.03-1000	1
	421.553	0.0009	270567	0.0009-1000	1		307.760	0.07	3321	0.07-950	2
Pr	460.733	0.009	2054	0.009-990	2	Mg	202.647	0.02	371	0.02-800	2
	411.846	0.06	2705	0.06-1000	1		279.079	0.14	302	0.14-750	3
	414.311	0.06	3394	0.06-1000	1		279.553	0.0006	54115	0.0006-1000	1
	417.939	0.24	2958	0.24-900	1		280.270	0.001	41616	0.001-1000	2
	422.535	0.10	2628	0.10-900	2		285.213	0.008	10847	0.008-1000	1

Silver (Ag)

The detection limit trend for the four lines of Ag is: 328.068 nm < 338.289 nm < 243.779 nm < 224.641 nm, respectively. The sensitivity trend is just reverse of the detection limit trend. Although the contribution of Dy on the 328.068-nm line is slightly higher than that of the 338.289-nm line, the 328.068-nm line was selected as the best analytical line for Ag by also keeping in mind the analytical performance result.

Boron (B)

The detection limit of all four lines of B (182.641 nm, 208.959 nm, 249.677 nm, and 249.773 nm) is almost similar, but the contribution of Dy on the 208.959-nm line is least, and the sensitivity of this line is higher than any other line of B. Hence, this line was selected as the best analytical line for the determination of B in a Dy matrix.

Chromium (Cr)

The contribution of Dy on the five lines of Cr follows the trend: 205.618 nm < 284.325 nm < 267.716 nm < 283.563 nm < 284.984 nm. Also, the detection limit of the 205.618-nm line is far better than the other lines of Cr. Thus, the 205.618-nm line was chosen as the best analytical line for the determination of Cr in a Dy matrix.

Effect of Dy Matrix on Ga, Ni, Gd, Ce, Nd, Al, In, Pb and Ba

These analytes are grouped on the basis of the minimum contribution of Dy on the line(s) of all of these analytes, which is greater than the minimum contribution on the line(s) of the previously described analytes as listed in Table VII. The analytical performance results of the following analytes are listed in Table VIII.

Gallium (Ga)

Of the three lines of Ga (417.206 nm, 294.364 nm, and 287.424 nm),

only the first one has a lower contribution of Dy with a higher tolerance level and best analytical performance. Hence, it was chosen as the best analytical line for Ga in a Dy matrix.

Nickel (Ni)

Some of the lines of Ni (227.021 nm, 231.604 nm, 232.003 nm, and 341.476 nm) have a closer value of detection limit, but only the 227.021-nm line interfered least. It is thus considered suitable for the determination of Ni in a Dy matrix.

Gadolinium (Gd)

The analytical performance results obtained for the four lines of Gd (335.047 nm, 335.862 nm, 336.223 nm, and 342.247 nm), are very similar. However, on the basis of the spectral interference results, the 335.047-nm line is considered best for the determination of Gd in a Dy matrix.

Cesium (Ce)

The detection limit for the five lines of Ce follows the trend: 413.765 nm < 413.380 nm < 393.373 nm < 418.660 nm < 448.691 nm. The 413.765-nm line shows a lower value of contribution from Dy compared to the other lines and hence, was selected for the determination of Ce in a Dy matrix.

Neodymium (Nd)

The contribution of Dy on all four lines of Nd (401.225 nm, 406.109 nm, 417.731 nm, and 430.358 nm) is very much the same and the detection limit follows the trend: 430.358 nm < 401.225 nm < 406.109 nm < 417.731 nm. The sensitivity follows the reverse trend. Thus, the 430.358-nm line was chosen for the determination of Nd in a Dy matrix.

Aluminum (Al)

Of the four analytical lines of Al (308.215 nm, 309.271 nm, 394.401 nm, 396.152 nm), the 309.271-nm line was not interfered by Dy, but

has a very high detection limit (3.03 mg/L). Based on the analytical performance and spectral interference study, the 394.401-nm line was selected for the determination of Al in a Dy matrix.

Indium (In)

The detection limit trend for the three lines of In follows the trend: 325.609 nm < 230.606 nm < 303.609 nm. It was found that the 325.609-nm line is much more interfered by Dy than the 230.606-nm line. Thus, the 230.606-nm line is considered more suitable for the determination of In in a Dy matrix.

Lead (Pb)

Among the four lines of Pb (220.353 nm, 261.418 nm, 283.305 nm, and 405.778 nm), the 283.305-nm line seems to be the best line for the determination of Pb in a Dy matrix, both from the analytical performance and spectral interference point of view.

Barium (Ba)

The 455.404-nm line of Ba possesses the best analytical performance compared to the other two lines (233.527 nm and 230.424 nm). The spectral interference results did not vary much. Hence, the 455.404-nm line was chosen for the quantitative determination of Ba in a Dy matrix.

Validation of Method for the Direct Determination of Analytes in a Dy Matrix

The aim of developing a method for the direct determination of analytes in the presence of a high-purity dysprosium matrix and selecting the best line(s) for each different analyte was validated using six sets of synthetic samples. They were prepared using commercially available standard reference materials of the individual elemental solutions. The samples were then fed to a hotter argon plasma, and the results obtained were analyzed without chemical separation.

TABLE V
Spectral Interference of Dy on Ca, Fe, Co, Cu, Tl, Ag, B, and Cr

Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)	Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)
Ca	396.847	3.06	6.1×10^{-3}	0.05	Cu	324.754	0.24	4.8×10^{-4}	100
	393.366	0.45	9.0×10^{-4}	0.05		327.396	0.30	5.8×10^{-4}	50
	317.933	1.40	2.9×10^{-3}	0.05		224.700	0.35	7.0×10^{-4}	10
	315.887	2.90	5.7×10^{-3}	200		219.226	6.40	1.3×10^{-2}	0.05
	183.801	5.91	1.2×10^{-2}	10		219.958	1.02	2.0×10^{-3}	5
Fe	422.673	0.30	6.0×10^{-4}	0.05	Tl	190.864	0.23	4.6×10^{-4}	50
	259.941	0.43	8.7×10^{-4}	1		276.787	#	-	0.05
	238.204	17.0	3.4×10^{-2}	0.05	Ag	338.289	0.36	7.2×10^{-4}	200
	239.562	0.22	4.4×10^{-4}	10		328.068	0.57	1.1×10^{-3}	50
	244.451	4.0	8.0×10^{-3}	1		224.641	8.0	1.6×10^{-2}	50
	261.187	1.2	2.4×10^{-3}	5	B	243.779	1.03	2.0×10^{-3}	10
	262.567	7.8	1.6×10^{-2}	10		249.773	0.53	1.0×10^{-3}	10
	262.829	2.5	5.0×10^{-3}	5		249.677	0.45	9.0×10^{-4}	50
	275.573	#	-	1	Cr	182.641	0.19	3.8×10^{-4}	200
	241.331	4.55	9.1×10^{-3}	10		208.959	0.13	2.6×10^{-4}	200
Co	373.486	3.30	6.5×10^{-3}	5		267.716	0.95	1.9×10^{-3}	10
	228.616	0.78	1.6×10^{-3}	1		205.618	0.18	3.6×10^{-4}	100
	238.892	0.34	6.9×10^{-4}	50		283.563	1.06	2.1×10^{-3}	10
	230.786	0.93	1.8×10^{-3}	5		284.325	0.65	1.3×10^{-3}	200
	237.862	0.16	3.1×10^{-4}	200		284.984	1.60	3.3×10^{-3}	10

*No interference.

#Significant spectral interference.

TABLE VI
Analytical Performance of Ca, Fe, Co, Cu, Tl, Ag, B, and Cr in Dy Matrix

Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	RSD (%)	Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynaic Range (mg/L)	RSD (%)
Ca	183.801	0.80	19	0.80-500	3	Cu	219.226	0.02	290	0.02-1000	1
	315.887	0.15	972	0.15-800	4		219.958	0.05	548	0.05-1000	1
	317.933	0.04	2936	0.04-1000	2		224.700	0.02	1310	0.02-1000	1
	393.366	0.0009	586502	0.0009-1000	1		324.754	0.002	41210	0.002-1000	1
	396.847	0.002	442492	0.002-1000	1		327.396	0.005	27554	0.005-1000	1
Fe	422.673	0.008	21893	0.008-1000	1	Tl	190.864	0.06	674	0.06-1000	3
	238.204	0.11	524	0.11-700	4		276.787	1.0	19	1.0-950	5
	239.562	0.02	1719	0.02-800	4	Ag	224.641	1.99	34	1.99-700	5
	241.331	0.49	137	0.49-800	3		243.779	0.16	360	0.16-800	4
	244.451	0.26	115	0.26-900	3		328.068	0.01	11359	0.01-1000	1
	259.941	0.03	1224	0.03-1000	2	B	338.289	0.02	6258	0.02-1000	1
	261.187	0.05	651	0.05-1000	1		182.641	0.03	554	0.05-1000	2
	262.567	0.68	93	0.68-1000	1		208.959	0.02	3080	0.02-1000	2
	262.829	0.42	123	0.42-750	2	Cr	249.677	0.05	787	0.05-1000	2
	275.573	0.21	222	0.21-900	1		249.773	0.02	1240	0.02-1000	2
Co	373.486	0.09	2086	0.09-1000	2		205.618	0.004	5765	0.004-1000	1
	228.616	0.05	588	0.05-950	1		267.716	0.11	545	0.11-800	2
	230.786	0.08	506	0.08-950	1		283.563	0.01	3220	0.01-1000	3
	237.862	0.02	1006	0.02-1000	1		284.325	0.35	1302	0.35-900	3
	238.892	0.05	1459	0.05-1000	1		284.984	0.22	385	0.22-900	3

TABLE VII
Spectral Interference of Dy on Ga, Ni, Gd, Ce, Nd, Al, In, Pb, and Ba

Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)	Ele- ments	Analytical Lines (nm)	Contribution From 500 mg/L of Dy	Correction Factor	Tolerance Level (mg/L)
Ga	417.206	0.71	1.4×10^{-3}	50	Nd	401.225	1.30	2.6×10^{-3}	5
	294.364	7.3	1.5×10^{-2}	1		430.358	1.02	2.0×10^{-3}	5
	287.424	12.0	2.4×10^{-2}	5		406.109	1.12	2.2×10^{-3}	5
Ni	231.604	1.06	2.1×10^{-3}	100	Al	417.731	0.97	2.0×10^{-3}	5
	221.648	0.86	1.7×10^{-3}	100		396.152	6.80	1.4×10^{-2}	1
	232.003	14.6	3.0×10^{-2}	0.05		394.401	3.02	1.0×10^{-2}	10
	227.021	0.71	1.4×10^{-3}	100		308.215	4.02	8.0×10^{-3}	1
	300.249	6.4	1.2×10^{-2}	10		309.271	*	-	500
Gd	341.476	#	-	0.05	In	230.606	3.0	5.8×10^{-3}	10
	342.247	4.7	9.3×10^{-3}	10		325.609	8.50	1.7×10^{-2}	1
	335.047	0.70	1.4×10^{-3}	2		303.936	11.7	2.3×10^{-2}	10
	336.223	2.0	4.0×10^{-3}	2	Pb	220.353	2.72	5.4×10^{-3}	1
Ce	335.862	10.9	2.2×10^{-2}	10		405.778	4.70	9.3×10^{-3}	100
	418.660	5.60	1.1×10^{-2}	5		283.305	2.34	4.7×10^{-3}	5
	448.691	#	-	500	Ba	261.418	16.7	3.3×10^{-2}	10
	413.765	1.32	2.6×10^{-3}	5		455.404	1.06	2.1×10^{-3}	10
	413.380	3.30	6.6×10^{-3}	5		233.527	2.43	4.8×10^{-3}	10
	393.373	#	-	500		230.424	0.90	1.8×10^{-3}	50

*No interference. #Significant spectral interference.

TABLE VIII
Analytical Performance of Dy on Ga, Ni, Gd, Ce, Nd, Al, In, Pb, and Ba

Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	RSD (%)	Ele- ments	Analytical Lines (nm)	D.L. (mg/L)	Sensitivity (counts/ mg/L)	Linear Dynamic Range (mg/L)	RSD (%)
Ga	287.424	0.43	155	0.43-750	3	Nd	401.225	0.06	3206	0.06-1000	1
	294.364	0.12	642	0.12-950	3		406.109	0.12	2168	0.12-950	3
	417.206	0.10	7204	0.10-950	3		417.731	0.24	1795	0.24-950	3
Ni	221.648	0.18	679	0.18-900	2	Al	430.358	0.04	3467	0.04-1000	1
	227.021	0.08	102	0.08-1000	2		308.215	0.04	1338	0.04-1000	2
	231.604	0.02	651	0.02-1000	1		309.271	3.03	2539	3.03-700	2
	232.003	0.04	548	0.04-1000	1		394.401	0.06	3141	0.06-1000	2
	300.249	0.36	440	0.36-700	3		396.152	0.02	9690	0.02-1000	2
Gd	341.476	0.01	4082	0.01-1000	1	In	230.606	0.18	517	0.18-950	2
	335.047	0.03	4845	0.03-1000	2		303.936	0.32	375	0.32-950	2
	335.862	0.06	2913	0.06-1000	2		325.609	0.06	1115	0.06-950	2
	336.223	0.06	3462	0.06-1000	2	Pb	220.353	0.17	219	0.17-900	2
Ce	342.247	0.03	4753	0.03-1000	2		261.418	0.90	53	0.90-900	3
	393.373	0.26	2821	0.26-900	3		283.305	0.08	547	0.08-1000	1
	413.380	0.07	2414	0.07-1000	1	Ba	405.778	0.27	707	0.27-1000	1
	413.765	0.06	2406	0.06-1000	1		230.424	0.14	745	0.14-900	3
	418.660	0.33	1968	0.33-900	3		233.527	0.23	364	0.23-900	3
	448.691	2.0	60	2.0-900	5		455.404	0.03	2900	0.03-1000	1

The elemental concentrations of six synthetic samples prepared for the present study were as follows:

1. Synthetic sample 1 (S 1): 0.1 mg/L of Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg in 500 mg/L of Dy.
2. Synthetic sample 2 (S 2): 1 mg/L of Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg in 500 mg/L of Dy.
3. Synthetic sample 3 (S 3): 0.2 mg/L of Ca, Fe, Co, Cu, Tl, Ag, B, and Cr in 500 mg/L of Dy.
4. Synthetic sample 4 (S 4): 2 mg/L of Ca, Fe, Co, Cu, Tl, Ag, B, and Cr in 500 mg/L of Dy.
5. Synthetic sample 5 (S 5): 1 mg/L of Ga, Ni, Gd, Ce, Nd, Al, In, Pb, and Ba in 500 mg/L of Dy.
6. Synthetic sample 6 (S 6): 5 mg/L of Ga, Ni, Gd, Ce, Nd, Al, In, Pb, and Ba in 500 mg/L of Dy.

From the results obtained, it is evident that Cd, Li, Mn, Sr, Pr, Na, Zn, La, Lu, and Mg can be estimated even at 0.1 mg/L in the presence of a dysprosium matrix. The analytes Ca, Fe, Co, Cu, Tl, Ag, B, and Cr were slightly interfered by Dy and can be estimated at 0.2 mg/L. The analytes Ga, Ni, Gd, Ce, Nd, Al, In,

Pb, and Ba, which were significantly interfered by Dy, can be estimated as low as 1 mg/L in the presence of 500 mg/L of Dy. The analyses results of the synthetic samples are listed in Tables IX-XI.

CONCLUSION

The systematic studies on the spectral interference of Dy on different analytes and the analytical performance of the different analytical lines of these analytes revealed that the Cd 226.502 nm, Li 670.780 nm, Sr 421.552 nm, Mg 279.553 nm, Mn 259.373 nm, Na 588.995 nm

TABLE IX
Validation of Method Using Synthetic Samples Containing Cd, Li, Sr, Mg, Mn, Na, Zn, La, Lu, and Pr in Dy Matrix

Elements	Analytical Lines (nm)	S1		S2	
		Actual Conc. (mg/L)	Amount After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount After Incorporating Correction Factor (mg/L)
Cd	226.502	0.1	0.098 ± 0.004	1	1.2 ± 0.4
Li	670.78	0.1	0.106 ± 0.005	1	0.98 ± 0.2
Sr	421.552	0.1	0.107 ± 0.003	1	1.1 ± 0.4
Mg	279.553	0.1	0.099 ± 0.002	1	1.0 ± 0.4
Mn	259.373	0.1	0.098 ± 0.005	1	0.99 ± 0.4
Na	588.995	0.1	0.100 ± 0.004	1	0.97 ± 0.4
	589.592	0.1	0.102 ± 0.004	1	0.95 ± 0.5
Zn	213.856	0.1	0.111 ± 0.004	1	1.11 ± 0.3
La	408.672	0.1	0.097 ± 0.005	1	1.23 ± 0.4
	379.478	0.1	0.098 ± 0.005	1	1.32 ± 0.4
Lu	261.542	0.1	0.095 ± 0.003	1	1.0 ± 0.5
Pr	417.939	0.1	0.099 ± 0.004	1	1.0 ± 0.5

TABLE X
Validation of Method Using Synthetic Samples Containing Ca, Fe, Co, Cu, Tl, Ag, B, and Cr in Dy Matrix

Elements	Analytical Lines (nm)	S3			S4		
		Actual Conc. (mg/L)	Amount Before Incorporating Correction Factor (mg/L)	Amount After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount Before Incorporating Correction Factor (mg/L)	Amount After Incorporating Correction Factor (mg/L)
Ag	328.068	0.2	0.75 ± 0.03	0.18	2	2.63 ± 0.13	2.06
B	208.959	0.2	0.37 ± 0.02	0.24	2	1.94 ± 0.11	1.81
Ca	393.366	0.2	0.64 ± 0.03	0.19	2	2.43 ± 0.08	1.98
Co	237.862	0.2	0.39 ± 0.04	0.23	2	1.96 ± 0.07	1.79
Cr	205.618	0.2	0.37 ± 0.02	0.19	2	2.20 ± 0.08	2.02
Cu	324.754	0.2	0.42 ± 0.02	0.18	2	2.30 ± 0.10	2.07
Fe	239.562	0.2	0.42 ± 0.03	0.2	2	2.17 ± 0.13	1.95
Tl	190.864	0.2	0.43 ± 0.03	0.2	2	2.19 ± 0.12	1.96

TABLE XI
Validation of Method Using Synthetic Sample Containing Ga, Ni, Ba, Gd, Nd, and Ce in Dy Matrix

Ele- ments	Analytical Lines (nm)	S5			S6		
		Actual Conc. (mg/L)	Amount Before Incorporating Correction Factor (mg/L)	Amount After Incorporating Correction Factor (mg/L)	Actual Conc. (mg/L)	Amount Before Incorporating Correction Factor (mg/L)	Amount After Incorporating Correction Factor (mg/L)
Ga	417.206	1	1.80 ± 0.07	1.09	5	5.69 ± 0.19	4.98
Ni	227.021	1	1.75 ± 0.09	1.04	5	5.76 ± 0.23	5.05
Ba	455.404	1	2.10 ± 0.11	1.04	5	7.00 ± 0.31	5.94
Gd	355.047	1	1.63 ± 0.08	0.93	5	5.6 ± 0.22	4.9
Nd	430.358	1	1.96 ± 0.10	0.94	5	6.2 ± 0.24	5.18
Ce	413.765	1	2.29 ± 0.09	0.97	5	6.4 ± 0.26	5.08
In	230.606	1	4.11 ± 0.15	1.11	5	8.1 ± 0.39	5.1
Pb	283.305	1	3.40 ± 0.13	1.06	5	7.5 ± 0.32	5.16
Al	394.401	1	3.96 ± 0.17	0.94	5	7.9 ± 0.33	4.88

and 589.592 nm, Zn 213.856 nm, La 408.672 nm and 379.478 nm, Lu 261.542 nm, and Pr 417.939 nm analytical lines were not interfered by Dy. These lines also showed the best analytical performance and hence, can be chosen for the determination of these analytes in the presence of a Dy matrix without chemical separation and without incorporation of the correction factors. The Ag 328.068 nm, B 208.959 nm, Ca 393.366 nm, Co 237.862 nm, Cr 205.618 nm, Cu 324.754 nm, Fe 239.562 nm, Tl 190.864 nm, Ga 417.206 nm, Ni 227.021 nm, Ba 455.404 nm, Gd 355.047 nm, Nd 430.358 nm, Ce 413.765 nm, Al 394.401 nm, Pb 283.305 nm, and In 230.606 nm analytical lines were found to be the best analytical lines of these elements. A simple, rapid ICP-AES-based method was developed for the determination these 27 analytes in a Dy matrix without chemical separation. The method was validated using synthetic samples prepared from commercially available standard reference materials of the individual solutions. The present approach appeared to be exciting and the analytical data were found to be in good agreement.

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