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Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

Trabajo de investigación para optar el Grado de Magíster en Física

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Resumen

El objetivo de este estudio fue verificar si un espectrómetro portátil de fluorescencia de rayos X (pXRF) puede reconocer las marcas de seguridad de los billetes originales que pueden ser reproducidas por los falsificadores. Se estudiaron billetes peruanos: 4 genuinos y 3 falsos, en 11 puntos de análisis cada uno, correspondiendo a 77 conjuntos de datos. El análisis de correlación de espectros entre los billetes originales fue 1.0, y no hubo correlación con los billetes falsos. El pXRF demuestra que dos marcas de seguridad fueron reproducidas por los falsificadores.

NOTA: Este Tema de Tesis ha sido aceptado y publicado como artículo científico por la revista "**Applied Radiation and Isotopes**" el 31 de enero de 2018, y se encuentra disponible online a partir del 02 de febrero del 2018. La autoría del artículo la comparto con la Dra. Celina Luizar Obregón, y la Mgt. Carmen Araujo Del Castillo (Q.E.P.D.), siendo yo, Marco Antonio Zamalloa Jara, el primer autor y autor de correspondencia.

Abstract

The aim of this study was to verify if a portable X-ray fluorescence (pXRF) spectrometer can recognize the security features in banknotes that are reproducible by counterfeiters. Peruvian Nuevo Sol banknotes were studied: 4 genuine and 3 fake ones, in 11 points of analysis for each one, at all 77 data set. The correlation analysis of spectra among original notes was 1.0, and there was no correlation with fake banknotes. pXRF prove that two security features were reproducible for counterfeiters.

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Nomenclature

Symbols

cor(x, y)	Function of Pearson’s linear correlation in RStudio
n	number of banknotes

Acronyms / Abbreviatios

BCRP	Banco Central de Reserva del Perú
CCD	Charge – Coupled Device camera
DIGESA	Dirección General de Salud Ambiental
IR	Infra - Red radiation
KeV	Kilo electron Volt
PCA	Principal Component Analysis
pXRF	portable X-ray fluorescence
SRM	Standard Reference Material
UV	Ultra - Violet radiation

1. Introduction

Falsification of currency banknotes is a fairly frequent illegal activity. The falsification of Dollars (CNBC, 2016; Reuters NBC News, 2016; Rusanov et al., 2009), Euros (Cabitza, 2012; Europol, 2012) and other currencies has forced governments to elaborate ever more sophisticated security features (Dwan, 2002), as for example, the development of micro-printing, the use of fluorescent inks, plastic paper and the use of substances reactive against UV and IR, among others. In Peru, the latest false banknotes are very difficult to identify for most people (Franklin, 2016) because falsifiers can reproduce many of the security features established by Peru´s Central Reserve Bank (BCRP) as are fluorescent images under UV light and chalcographic marks for touch recognition (BCRP, 2016). This problem affects low-income populations and tourists who are not familiar with the national money. Tourism is one of the most important financial income sources in Cusco, Peru.

Peruvian counterfeiters have managed to reproduce high quality forgeries of paper currency, one being the highest value banknote, the 200 Nuevos Soles bill, said to be the ‘best fake’. Counterfeited banknotes present a texture very similar to that of a genuine banknote. They contain metallic threads with reflections and colorful fluorescent designs very similar to those expected to see in a UV detector for a genuine bill. Furthermore, the current development of printing technology allows the falsifiers to obtain a higher image quality, with details that are very similar to those present on genuine banknotes.

These and other aspects make the identification of fake banknotes difficult in Peru, and highlight the necessity of developing security marks that cannot easily be reproduced, and which, in turn, are easy to identify by common people. This problem also creates the need to develop new techniques that differentiate genuine banknotes from false ones.

In literature, the use of techniques to recognize fraudulent banknotes has been reported. For example, there is the use of image analysis for texture identification (Hassanpour and Farahabadi, 2009; Cao, S. Nie, X. and Cheng, Z., 2012), intelligent recognition of paper currency systems based on image analysis (García-Lamont et al., 2012; Sargano et al., 2014), near infrared spectroscopy to characterize the cotton paper currency (Dale and Klatt, 1989), Raman spectroscopy to identify the organic nature of inks in banknotes (Jelovica Badovinac et al., 2010), and among others (Roy et al., 2015). The X-ray fluorescence spectroscopy (XRF) is a non-destructive technique that allows simultaneous identification of several elements, in short time (Cesareo et al., 2007). XRF was used for the identification of lead in American Dollar banknotes, as a drying agent, before the 90s (Nir-El, 1994), and recently, to compare dyes used in stamps and one Lira banknotes, in Croatia. Appoloni and Melquiades (Appoloni and Melquiades, 2014) also showed that portable the X-ray fluorescence spectroscopy (pXRF) is a useful non-invasive technique, in the study of paper currency. In this sense, the present study intends to demonstrate that pXRF can also be used to identify fake Nuevos Soles banknotes and recognize the security features in banknotes that are reproducible by counterfeiters.

2. Material and methods

The analyzed samples were collected in the city of Cusco, and correspond to the 200 Nuevos Soles banknotes in circulation (BCRP, 2015). It is the highest denominator banknote in circulation, for which reason also makes it the most lucrative to falsify. Three of them were counterfeited (**I**, **III** and **V**), and four were genuine (**II**, **IV**, **VI** and **VII**). Each bill was taken randomly and was already in circulation in the economy. The origins of the fake bills are unknown.

A visual evaluation, under normal illumination, of the original banknotes was performed and, based on their color diversity 11 points were selected for pXRF analysis: six on the front side (from 1 to 6), and five on the reverse side (from 7 to 11) as shown in Figure 1. For each point there were two kinds of data: first, the spectra with 2048 values (channels), and second, the element concentration in ppm.

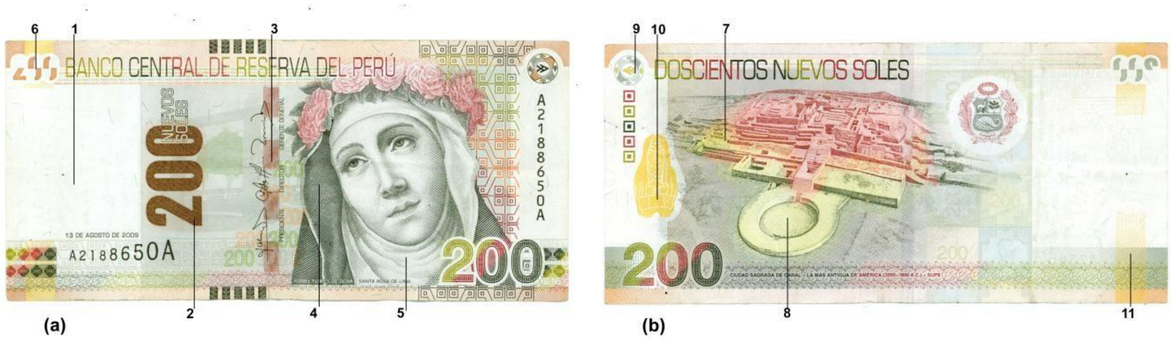

Figure1. pXRF analysis points for the two hundred Nuevos Soles banknotes, (a) front side, and (b) reverse side.

For the pXRF analysis a handheld Premium DELTA Olympus portable fluorescence spectrometer was used, with a broad area SDD silicon drift detector, Rh 4W X-Ray tube and, 200 μA maximum intensity. The analysis was performed in *Soil* mode. The equipment shot at the sample three times (three beams) consecutively at exactly the same point while maintaining equal geometry. The experimental conditions were acquisition time, tube voltage, and tube current, as follows, beam-1: 15s, 40 KeV, 67 μA; beam-2: 20s, 40 KeV, 34 μA and, beam-3: 30s, 15 KeV, 78 μA respectively.

Before the experiment, the equipment was checked to make sure it was working correctly using a 316 Stainless Steel Calibration Check Reference Coin. For all the experiments a stand workstation was used. The x-ray gun was placed under the workstation and faced upwards, then the bill was placed on the shooting window. Through a mini CCD camera (model DP-600-CC) the irradiated area could be observed, that corresponded to a circular diameter of 8mm. The spectra and the element concentration were obtained using the Innov-X Delta software.

The 11 points analyzed on each bill correspond to 77 sets of data. In the case of the spectral analysis, 77 spectra were considered, each containing 2048 data, corresponding to 2048 channels (1 to 2048), and the respective number of counts per channel. Each channel is associated with an energy value (0 to 40 KeV). This involves the manipulation of 157696. In addition, the Soil mode of the pXRF spectrometer provided three spectra for each point, since three beams were used, making the initial total amount of data about 473088. However, the preliminary analysis showed that the elements present could be studied with the third beam (0 to 40 KeV), which significantly decreased the amount of data used.

During the experiment, the bills were mixed in a way that they could not be recognized as originals or false. A set of XRF chemical emissions were considered to characterize and identify the original bill, therefore the genuine bills should have equal or similar emissions, because in theory they came from the same manufacturer and so should show equal correlations (*cor (x,y) = 1*) between spectral intensities for each energy.

Then, applying R-Studio v. 0.99.486 the correlation between all the spectra using the function “cor (x,y)” was calculated. That operates as a default Pearson’s linear correlation, and measures the lineal relationship between two quantitative random variables and is independent from the scale of measurement of the variables, which correspond to different spectra. Thus, a matrix with 2048 rows (energy channels) was constructed per 77 columns (counts or intensities) of the 11 analysis points for each of the 7 banknotes. Only beam-3 spectra counts were used, since they contained all the elements of interest. To find the number of correlations in the algorithm of the program in R, the equation **[n (n-1) / 2]** was used, where n is the number of banknotes (n = 7), obtaining 21 correlations for each point, making a total of 231 correlations (21 x 11 analysis points).

After observing the results, the correlations between the selected points were almost identical on the authentic bill, despite being well-used and already in-circulation. From this, we could conclude our experiments on the genuine notes, as they all showed the same result. The software Innov-X Delta reported the presence of the elements, the spectral peaks were matched to emission energy tables, after that the presence of the elements were evaluated and confirmed.

Furthermore, in order to validate the results, it is necessary to use matrix standards similar to paper money with a thin film geometry. However, we only had the SRM® 2710a Montana I Soil and the SRM® 2711a Montana II Soil standards that feature infinitely thickness geometry. These were placed in the stand workstation of the pXRF and analysed under the same conditions as the bills. Then, the standards were used only with the intention of demonstrating the validity of the results reported by the equipment.

The PCA multivariate analysis used Pirouette 4.5 and the concentrations obtained from three beams of Innov-X Delta software, for the 15 identified elements. These were considered as variables, meanwhile the 11 points, in each one of the 7 banknotes, constituted a total of 77 samples. A mean centering pre-processing was performed, to mitigate the influence of the Ca and Ti variables magnitude, and 7 factors were considered as a maximum.

3. Results and discussion

Twelve (12) elements were identified using the genuine banknotes pXRF elemental analysis: Ca, Ti, Cl, Zn, Cu, Fe, K, Sr, Mn, Zr, Cr, and S (Table 1). These elements can be separated into three groups, the first, with mayor intensities: Ca and Ti. The second group, with middle intensities: Cl, Zn, Cu, Fe, and K. The third group with lower intensities: Sr, Mn, Zr, Cr, and S. Lead (Pb) was found only in two of four original bills.

Table 1.
Average intensity in beam 3 (Count / s) of the elements present in the original banknotes for each analysis point.

	Mayor intensities		Middle intensities				
Point	Ca	Ti	Cl	Zn	Cu	Fe	K
1	31360±3860	44375±926	4079±560	3800±152	2087±111	1941±261	1433±558
2	31728±5170	38686±689	3950±295	3845±218	2247±61	2086±238	1345±425
3	42480±7253	43742±1590	6072±427	3651±196	2124±151	2199±278	1117±258
4	51857±8260	38234±1491	3745±273	3633±93	2928±107	2149±239	1494±442
5	37424±5596	39448±1363	4437±237	3734±127	2397±106	1987±216	1174±383
6	36408±4866	39399±1579	4971±518	3665±49	2021±35	1724±191	1102±306
7	42836±8005	37371±568	4147±356	3669±154	2303±99	1915±304	1158±411
8	37394±6720	38130±1119	4502±226	3741±153	2301±91	2007±301	1209±426
9	36009±4332	37907±1298	4784±246	3646±69	2116±59	2034±473	1291±278
10	35404±4922	39064±543	4577±408	3704±144	2085±84	2057±409	1304±566
11	35552±5738	37578±2021	4429±510	3514±172	2240±120	1978±162	1312±462

	Lower intensities				
Point	Sr	Mn	Zr	Cr	S
1	702±25	362±8	206±8	142±18	120±13
2	722±26	400±33	215±3	139±9	157±29
3	681±21	419±68	216±11	136±22	147±14
4	716±35	594±173	224±2	140±13	188±8
5	719±33	431±72	225±1	147±5	145±7
6	686±35	346±16	202±5	127±12	127±13
7	687±16	442±83	203±4	137±7	145±10
8	717±41	395±39	205±5	131±16	141±9
9	736±16	379±16	199±15	133±10	136±9
10	695±12	398±60	214±3	132±16	130±20
11	661±31	415±62	199±20	132±7	125±17

These results coincide with those reported by Appoloni and Melquiades (2014) who highlighted the presence of Fe, Ti, Ca, Sr and Zr in a R/.50.00 Brazilian Reales currency banknote, and in a USD $50.00 American Dollar banknote, they reported Fe, Ti, Ca and Zn and, finally, the presence of Ti, Ca and Y, in a €50.00 Euro banknote. The above-mentioned authors indicate that these banknotes coincide in the presence of titanium´s white pigment in paper currency.

The false banknotes show a different elemental composition (Table 2). 15 elements were identified and can be divided into two groups: The first is composed of the same elements as in the originals: Ca, Cl, Ti, K, S, Fe, Mn, Zn, Sr, Cr, Cu and Zr. The second group can be constituted by As, Y, Pb, and where As and Y show up once or twice. Meanwhile lead is present in more than 7 of the 11 analyzed points in all the fake bills.

Table 2.
Elemental composition (ppm) found in the false banknotes

First Group- Same elements as in the original banknotes

Point		Ca	Cl	Ti	K	S	Fe	Mn	Zn	Sr	Cr	Cu	Zr
1	Bill-I	146456±621	44980±292	27758±123	2308±43	1349±196	167±8	77±3	61±2	65±2	23±2	14±2	6±1
1	Bill-III	183336±802	21838±205	62073±271	1752±44	1064±214	112±7	143±3	41±2	74±2	25±3	14±2	4±1
1	Bill-V	158041±685	34009±256	54517±236	3736±54	1099±205	119±7	124±3	61±2	67±2	26±2	18±2	ND
2	Bill-I	94194±414	160500±775	34911±152	6712±68	1693±224	286±9	56±2	45±2	66±2	11±2	13±2	5±1
2	Bill-III	157636±677	89960±490	32818±145	789±34	2237±228	93±6	116±3	46±2	78±2	341±4	9±2	ND
2	Bill-V	142999±610	82227±452	30035±132	2192±42	3018±226	135±7	106±3	67±2	70±2	663±6	13±2	ND
3	Bill-I	120324±515	45916±295	28032±123	1919±40	811±181	155±8	96±3	62±2	61±2	22±2	9±2	8±1
3	Bill-III	123737±519	15968±158	34552±147	1504±37	1290±175	134±7	127±3	54±2	69±2	26±2	14±2	ND
3	Bill-V	142296±584	24609±195	29037±123	1831±38	1678±185	144±7	113±3	49±2	67±2	32±2	16±2	ND
4	Bill-I	143139±595	36055±247	21837±97	1545±37	895±181	193±8	84±3	47±2	67±2	18±2	16±2	5±1
4	Bill-III	172966±733	23229±198	33387±146	1081±36	931±195	134±7	192±3	45±2	76±2	21±2	14±2	ND
4	Bill-V	165602±705	40082±275	32318±142	2690±47	1360±204	139±7	104±3	57±2	68±2	19±2	14±2	ND
5	Bill-I	90335±379	211751±934	15583±70	794±28	1946±224	153±7	79±2	40±2	69±2	ND	11±2	8±1
5	Bill-III	130943±548	46741±294	26724±116	1079±33	8274±258	214±9	366±4	45±2	73±2	14±2	10±2	ND
5	Bill-V	137001±571	110642±554	26737±116	1664±37	1529±212	125±7	109±3	69±2	64±2	8±2	7±2	ND
6	Bill-I	150489±624	36013±248	25666±112	1737±38	1181±188	171±8	83±3	75±2	69±2	24±2	9±2	6±1
6	Bill-III	187094±795	22891±200	43078±187	1838±42	1216±207	104±7	122±3	48±2	78±2	28±2	9±2	ND
6	Bill-V	187009±831	31813±252	45986±207	1893±45	1715±226	118±7	128±3	64±3	70±2	30±2	8±2	4±1
7	Bill-I	170084±733	54492±342	34407±153	2623±47	1999±220	145±7	81±3	55±2	65±2	44±2	10±2	8±1
7	Bill-III	193236±828	31531±241	37296±165	2155±45	1388±214	124±7	120±3	56±2	76±2	28±2	18±2	ND
7	Bill-V	170802±727	41331±281	35323±155	3580±52	1795±212	146±7	108±3	64±2	68±2	35±2	23±2	ND
8	Bill-I	153338±660	68476±399	25700±116	1122±36	1444±210	131±7	75±3	41±2	68±2	15±2	12±2	7±1
8	Bill-III	162566±686	41575±278	32817±143	1034±35	5433±244	177±8	261±4	53±2	76±2	17±2	9±2	ND
8	Bill-V	160215±670	63862±370	32058±139	3512±50	1665±210	135±7	99±3	66±2	67±2	15±2	14±2	ND
9	Bill-I	155915±659	53264±328	29936±131	1478±38	1225±200	147±7	76±3	47±2	60±2	20±2	14±2	6±1
9	Bill-III	195459±826	34570±252	38133±166	1977±43	1580±216	112±7	109±3	52±2	76±2	21±2	7±2	ND
9	Bill-V	169972±715	35833±254	34325±149	2467±45	930±198	120±7	103±3	48±2	68±2	24±2	14±2	ND
10	Bill-I	167759±716	50949±323	28627±128	1876±41	1379±208	159±8	78±3	56±2	71±2	24±2	7±2	9±1
10	Bill-III	166097±715	60685±368	33807±150	1898±42	1897±219	120±7	125±3	53±2	77±2	21±2	13±2	ND
10	Bill-V	134688±570	107414±549	31592±137	2891±46	1843±217	118±7	106±3	53±2	64±2	27±2	19±2	ND
11	Bill-I	185394±772	18089±169	27564±121	1571±39	1055±195	165±7	91±3	98±3	77±2	25±2	12±2	9±1
11	Bill-III	198976±845	24679±208	40205±175	1578±41	1599±215	98±7	120±3	56±2	78±2	29±2	7±2	ND
11	Bill-V	163518±702	40428±280	42117±184	5205±62	1813±213	143±7	124±3	61±2	71±2	36±2	30±2	ND

Second Group- Elements (ppm) identified just once or twice but in different false banknotes

	Bill-I		Bill-III			Bill V	
Point	As	Pb	As	Y	Pb	As	Pb
1	ND	ND	ND	ND	ND	ND	ND
2	ND	5±1	6±1	ND	16±1	5±1	14±1
3	ND	ND	ND	ND	9±1	ND	13±1
4	ND	5±1	ND	567±10	7±1	ND	8±1
5	ND	6±1	ND	1157±18	5±1	ND	ND
6	ND	4±1	ND	ND	6±1	ND	7±1
7	6±1	12±1	ND	6±1	9±1	ND	10±1
8	ND	4±1	ND	650±11	4±1	ND	4±1
9	ND	4±1	ND	ND	6±1	ND	7±1
10	ND	5±1	ND	ND	9±1	4±1	11±1
11	ND	ND	3±1	ND	8±1	ND	12±1

It is logical to expect that the spectral correlation on each point should be 1.0 with all original banknotes. The pXRF analysis confirms the previous statement. Table 3 shows the spectral correlation of the elements identified by pXRF for the false banknotes (**I, III** and **V**) and the genuine ones (**II, IV, VI** and **VII**). For example, in the second analysis point (**2**), the correlation between the false banknote (**I**) and the genuine one (**II**) is 0.81, meanwhile the correlation, at the same point, between the original banknotes **II-IV, II-VI, II-VII, IV-VI, IV-VII** and **VI-VII** is 1.

Table 3.
Spectral correlation in the eleven points, between the original (II, IV, VI, VII) and false (I, III and, V) banknotes

Banknotes Correlation	Analysis points										
	1	2	3	4	5	6	7	8	9	10	11
Bill I x II	0.97	0.81	0.99	1	0.67	0.97	1	0.98	0.99	0.98	0.93
Bill I x III	0.97	0.86	0.97	0.99	0.53	0.99	0.99	0.93	0.99	1	1
Bill I x IV	0.97	0.8	0.99	1	0.66	0.95	1	0.99	0.98	0.98	0.94
Bill I x V	0.98	0.86	0.98	1	0.87	0.99	1	1	0.99	0.92	0.98
Bill I x VI	0.96	0.75	0.99	0.99	0.64	0.98	1	0.99	0.99	0.98	0.96
Bill I x VII	0.95	0.77	0.99	1	0.69	0.96	0.99	0.99	0.98	0.97	0.93
Bill II x III	0.95	0.98	0.93	0.99	0.84	0.94	0.98	0.92	0.96	0.99	0.94
Bill II x IV	1	1	1	1	1	1	1	1	1	1	1
Bill II x V	0.98	0.98	0.94	1	0.95	0.95	0.99	0.99	0.97	0.95	0.98
Bill II x VI	0.99	1	1	1	1	1	1	1	1	1	1
Bill II x VII	1	1	1	1	1	1	1	1	1	1	1
Bill III x IV	0.95	0.97	0.95	0.99	0.83	0.93	0.98	0.93	0.95	0.99	0.96
Bill III x V	1	1	1	0.99	0.79	1	1	0.94	1	0.94	0.99
Bill III x VI	0.97	0.97	0.94	0.99	0.84	0.96	0.99	0.93	0.96	0.99	0.97
Bill III x VII	0.94	0.97	0.95	0.99	0.83	0.94	0.97	0.92	0.96	0.98	0.95
Bill IV x V	0.97	0.98	0.96	1	0.94	0.95	0.99	0.99	0.96	0.96	0.99
Bill IVx VI	0.99	1	1	1	1	1	1	1	1	1	1
Bill IV x VII	1	1	1	1	1	1	1	1	1	1	1
Bill Vx VI	0.98	0.97	0.95	1	0.93	0.97	1	0.99	0.97	0.94	0.99
Bill Vx VII	0.96	0.97	0.95	1	0.95	0.95	0.99	0.99	0.97	0.96	0.98
Bill VI x VII	0.99	1	1	1	1	1	0.99	1	1	1	1

It was observed that any one of the correlations, between the genuine banknotes (Figure 2a), is always equal to 1, with the exception of the correlations between the **II-VI, IV-VI** and **VI-VII** banknotes, at point 1, which could be due to the banknote´s contamination and wear from being in circulation. This shows the fabrication reproducibility of the studied original banknotes, and the potential pXRF as an applicable technique in the forensic analysis sustained in the elemental analysis.

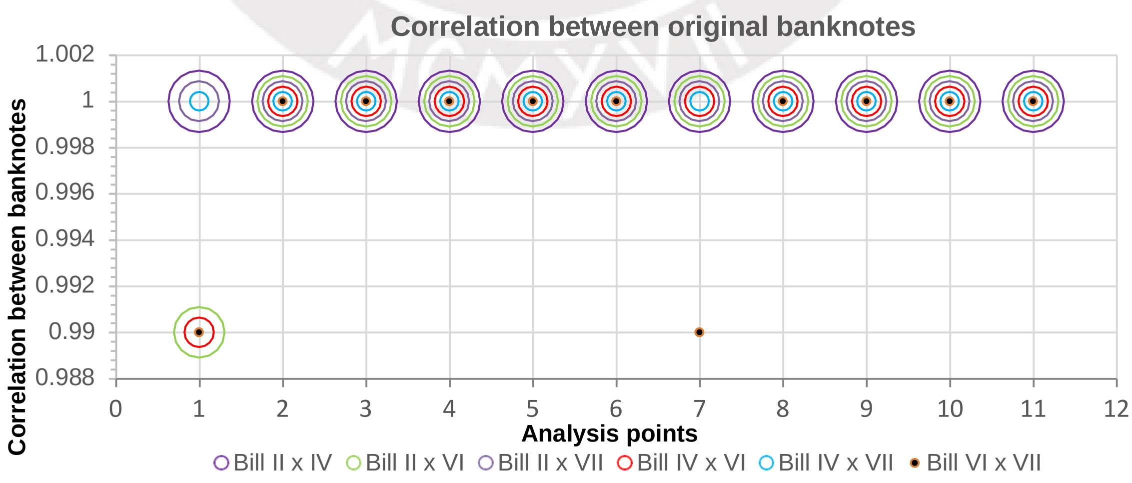

Figure 2a. Spectral correlation in each one of the eleven analysis points between the originals banknotes (II, IV, VI and VII).

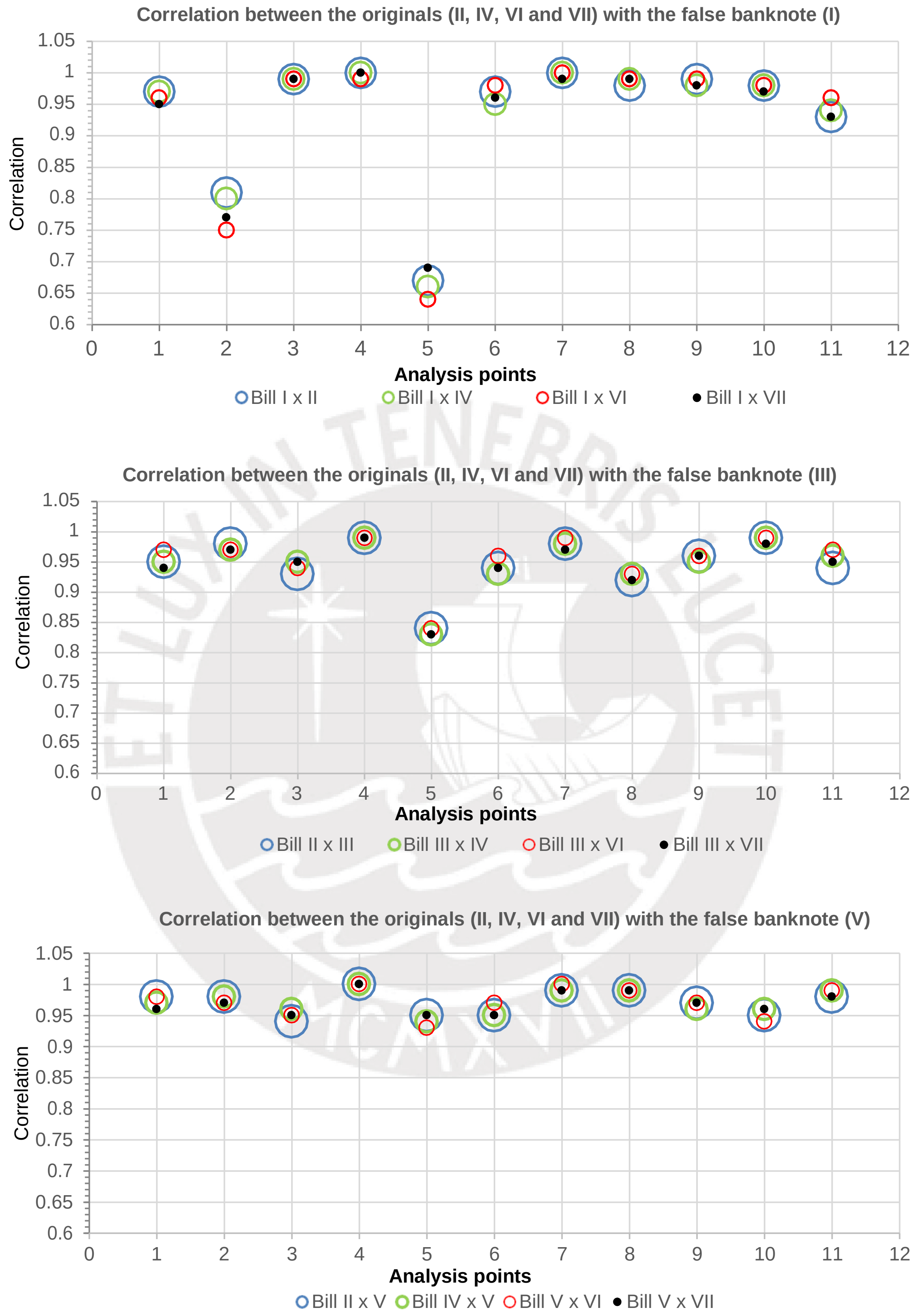

Figure 2b. Spectral correlation in each one of the eleven analysis points between the originals (II, IV, VI and VII) banknotes and false ones I, III and V.

In a similar way, it was observed that the points **4** and **7** present high original/false Pearson correlations, and even give a value equal to one between false banknotes (**I** and **V**), implicating that these points could be falsified with greater ease (Figure 2b).

False notes generate different emissions than the authentic ones, which is shown with correlations between 0.65 and 0.8. Likewise, there are points of analysis in counterfeit notes with correlation in respect to the original, close to 1. Thus, we consider that these points can be reproduced by counterfeiters. From Figure 2b, we can conclude that the best falsification corresponds to bill **V**, which has correlations between 0.93 and 1 with the original bills.

The pXRF data show that point **5** is the most difficult one to reproduce (Figure 2b). Therefore, one can state that pXRF is a technique that allows for orientation of the type of security feature to be developed in banknotes.

In Table 3, it is observed that the difference in correlation obtained from pXRF, between real banknotes is of a centesimal (0.01), considering the banknotes were not new, and that they were in circulation, these values might reflect a certain degree of contamination proceeding from manipulation for being in circulation. The use of new banknotes, in the study, would give correlations equal to 1, as results. Thus, it is possible to assert that pXRF is a technique that not only allows identifying false Soles banknotes, but, also, the development of new ones.

The result of the principal components analysis (100 % of accumulated variance), based on the concentration obtained by pXRF, presents the separation of two groups: genuine and false. Although samples **b1-2** and **b1-5** (points 2 and 5 in banknote **I**, respectively) could look like outliers, their exclusion does not conduce to a better PCA result. The same happens with the exclusion of Ca, Ti and Cl.

The 3D graphic of factors (Figure 3a) shows the separation of the two groups: Originals in red (**B2, B4, B6** and **B7**), and false in brown (**b1, b3** and **b5**). The loadings' graphic (Figure 3b) shows, that the presence of Ca is important in the false banknotes' characterization, as well as that of Titanium, in the genuine banknotes. This fact could be related to the type of paper used and Titanium ink previously reported. The presence of Calcium (Figure 4), in the genuine banknotes is notably lesser than in the false ones.

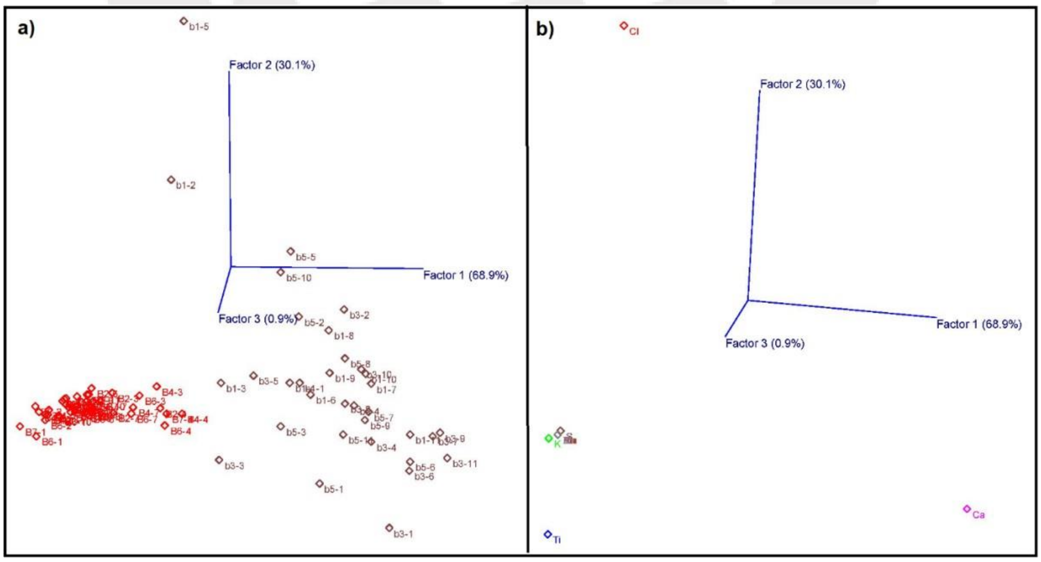

Figure 3. Principal components analysis 3D graphic of (a) scores and (b) loadings. Original banknotes are in red (B2, B4, B6 and B7) and false banknotes in brown (b1, b3, b5) with their eleven sampling points.

Banknote **I** has a different presence of Chlorine to that observed in other fake bills. Point 2 (**b1-2**) and point 5 (**b1-5**) are characterized by their content in this element (16.1 % and 21.2%) respectively.

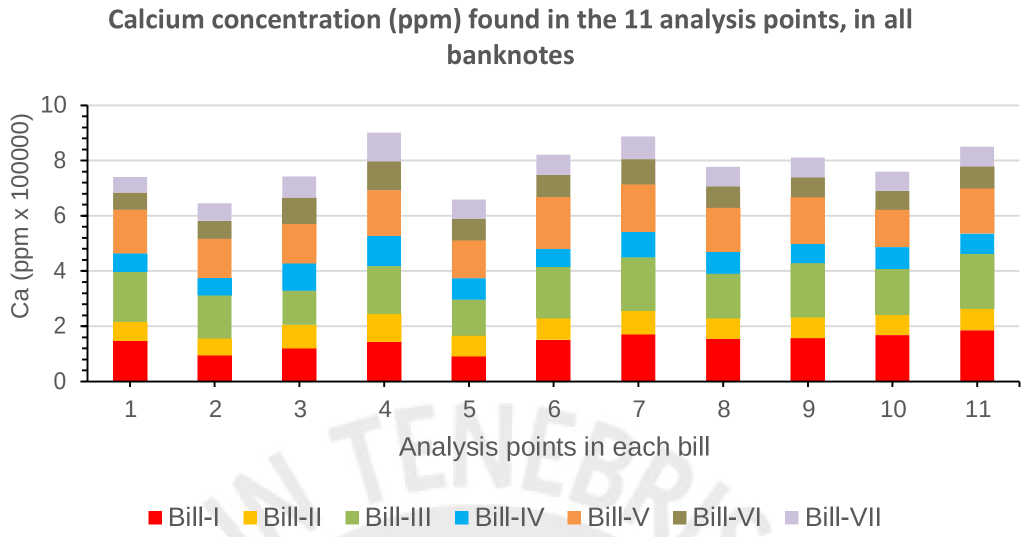

Figure 4. Calcium concentration (ppm) found in the 11 analysis points, in all banknotes

On the other hand, in point **5**, the false banknotes also show a different elemental composition to that of the genuine ones. That is to say that, although under UV light, these points could seem red to the human eye, and identical to the original. However, the pXRF emission shows that they correspond to different energies, thus identifying the falsification.

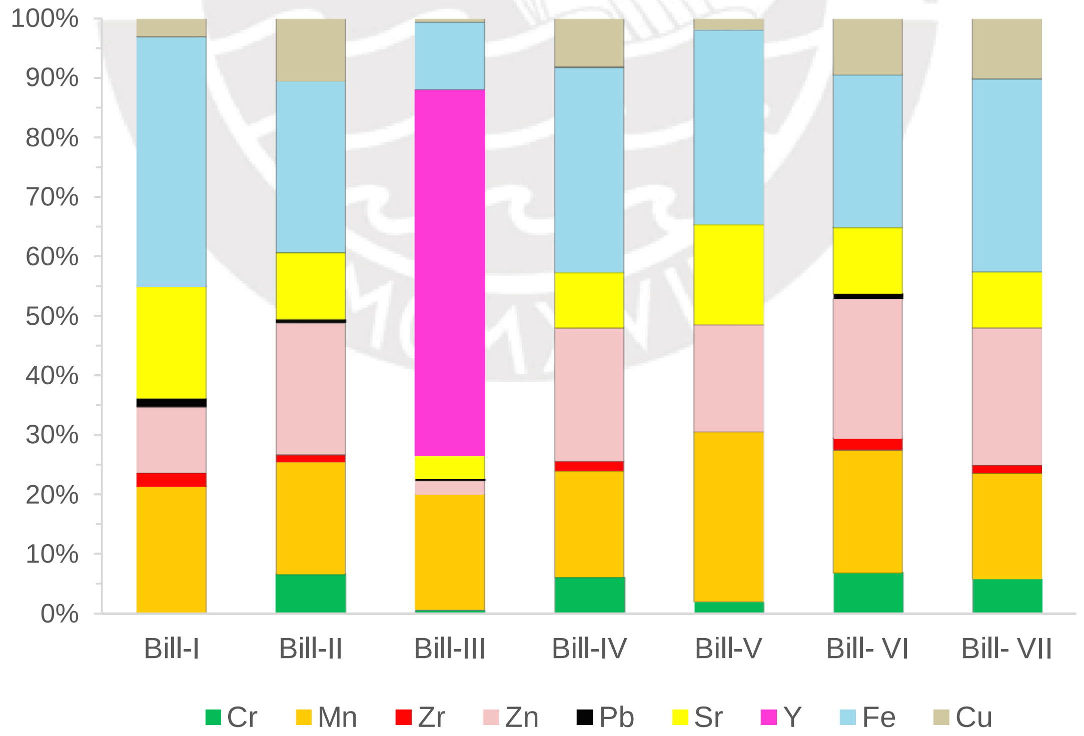

Figure 5. Minority elements in point 5, in all banknotes

It is known that the trace elements distribution, in different samples, tends to relate to the sample´s origin. In this sense, Figure 5 shows the variability of the minority elements profile, the false banknotes (**I, III** and **V**) composition is different to the genuine banknotes (**II, IV, VI** and **VII**).

In Table 4 we compare our results from the experiments using the specified values from Standard Reference Material SRM 2710a Montana I Soil and SRM 2711a Montana II Soil. The experiment values correspond to the average of three measurements made under the same condition for all the points analyzed on the 200 Nuevos Soles bill. The table shows that the experiment concentrations were very close to the certified values, which validates the results obtained by the pXRF.

Table 4.
Values of elemental composition in SRM 2711a and SRM 2710a obtained by pXRF

	SRM 2711a	
Element	**Experimental (%)**	**Certified Values (%)**
K	2.75 ± 0.02	2.53 ± 0.10
Ca	2.74 ± 0.02	2.42 ± 0.06
Ti	0.319 ± 0.030	0.317 ± 0.008
Fe	2.41 ± 0.02	2.82 ± 0.04
Element	**Experimental (ppm)**	**Certified Values (ppm)**
Cr	37 ± 3	52.3 ± 2.9
Mn	640 ± 6	675 ± 18
Cu	125 ± 4	140 ± 2
Zn	370 ± 6	414 ± 11
As	125 ± 8	107 ± 5
Sr	236 ± 5	242 ± 10
Y	35 ± 2	-
Zr	402 ± 8	-
Pb	1322 ± 11	-
	SRM 2710a	
Element	**Experimental (ppm)**	**Certified Values (ppm)**
Sr	262±6	255 ± 7
Pb	5299±37	5520 ± 30

Moreover, pXRF let us identified the presence of small quantities of some toxic elements in the false banknotes: Cr, Pb, and As (Table 5). Chrome was found in point 2 of all fake bills, in the false banknotes **Bill-III** (341 ppm) and in **Bill-V** (663 ppm), it exceed the limit for toys and desk utensils (60 ppm), allowed by Dirección General de Salud Ambiental-DIGESA in Peru (DIGESA, 2008). Pb and As are under the permissible limits.

Table 5. Values (ppm) of some toxic elements in the false banknotes (I, III and V)

		Cr		**Pb**		**As**
Maximum value		-	Bill-I:	12±1	Bill-I:	6±1
all studied banknotes	Bill-III:	341±4	Bill-III:	16 ±1	Bill-III:	6±1
	Bill-V:	663±6	Bill-V:	14±1	Bill-V:	5±1
Maximum limit allowed by DIGESA in toys		**60**		**90**		**25**

4. Conclusions

The results from the semi quantitative elemental analysis, using pXRF, show that the chemical composition of the ink used in the false banknotes is different to that of original ones. The data analysis allows an insight into the pXRF´s potential, as a technique applicable to high quality fraudulent paper currency detection and also allows identifying which are the security marks that are easily and more faithfully reproduced by falsifiers. The use of principal components analysis, in the data processing, also allows an insight into the pXRF's applicability in this field.

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Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

Artículo para optar el Grado de Magister

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Resumen

El objetivo de este estudio fue verificar si un espectrómetro portátil de fluorescencia de rayos-X (pXRF) puede reconocer las marcas de seguridad de billetes originales y si pueden ser reproducidas por falsificadores. Se estudiaron 7 billetes: 4 originales y 3 falsos, en 11 puntos de análisis cada uno, correspondiendo a 77 conjuntos de datos. El análisis de correlación espectral fue 1.0 entre originales, y menor con los falsos. El pXRF muestra que dos marcas de seguridad fueron vulneradas.

Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

Contenido

Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

1. Introducción

La falsificación es una actividad ilegal frecuente: dólares (CNBC, 2016; Reuters NBC News, 2016; Rusanov y otros, 2009), Euros (Cabitza, 2012; Europol, 2012) y otras, han obligado a los gobiernos a elaborar marcas de seguridad cada vez más sofisticadas (Dwan, 2002). Así tenemos por ejemplo, el desarrollo de microimpresiones, el uso de tintas fluorescentes, el papel plástico, el uso de sustancias reactivas frente a radiación UV e IR, etc.

1. Introducción

En Perú, los falsificadores han podido reproducir varias marcas de seguridad establecidas por el BCR (Franklin, 2016), así como imagenes fluorescentes a luz UV y marcas calcograficas para reconocimiento tactil (BCRP, 2016). Esto dificulta su identificación y afecta a la población y a los turistas quienes no estan familiarizados con billetes peruanos.

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1. Introducción

Así también, han logrado reproducir billetes de 200 Soles, con un alto grado de maestría. Estos poseen hilos metálicos con reflejos, diseños fluorescentes y presentan texturas similares a un billete original. Además, la tecnología actual de impresión permite a los falsificadores obtener una calidad de imagen superior, con detalles que son muy similares a los billetes originales.

1. Introducción

Estos hechos resaltan la necesidad de desarrollar marcas de seguridad que no puedan reproducirse fácilmente y que, a su vez, sean fáciles de identificar por la gente común. Este problema también crea la necesidad de desarrollar nuevas técnicas que diferencien los billetes auténticos de los falsos.

1. Introducción

Para reconocer billetes falsos se han desarrollado técnicas, como: el análisis de imágenes para identificación de texturas (Hassanpour y Farahabadi, 2009; Cao, et al., 2012), sistemas inteligentes de reconocimiento de papel moneda por imágenes (García-Lamont et al., 2012; Sargano et al., 2014), espectroscopia de infrarrojo cercano para caracterizar el papel (Dale y Klatt, 1989),

1. Introducción

y últimamente, la espectroscopia Raman para identificar tintas (Jelovica Badovinac et al. 2010), entre otros (Roy et al., 2015).

La espectroscopía XRF es una técnica no destructiva que permite la identificación simultánea de varios elementos, en poco tiempo (Cesareo et al., 2007).

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1. Introducción

XRF se usó para identificar plomo en dólares americanos (Nir-El, 1994), y recientemente, para comparar tintes en sellos y billetes de Lira, en Croacia. Appoloni y Melquiades (2014) mostraron que la espectroscopía pXRF es una técnica útil y no invasiva, en el estudio del papel moneda.

El presente estudio pretende demostrar que el pXRF se puede utilizar para identificar billetes falsos y conocer las marcas de seguridad que son reproducibles por los falsificadores.

Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

2. Materiales y metodología

Las muestras analizadas fueron recolectadas en la ciudad de Cusco y corresponden a billetes de 200 nuevos soles en circulación (BCRP, 2015). Ser el billete de mayor denominación lo convierte en el más atractivo para los falsificadores. Usamos 3 billetes falsos (I, III y V) y 4 billetes genuinos (II, IV, VI y VII). Los orígenes de los billetes falsos son desconocidos.

Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

2. Materiales y metodología

Se seleccionaron 11 puntos para analizar: seis en el anverso (de 1 a 6) y cinco en el reverso (de 7 a 11) como se muestra en la Figura 1. Para cada punto existen dos tipos de datos: el primero corresponde a los espectros, y el segundo a la concentración de los elementos en ppm.

2. Materiales y metodología

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2. Materiales y metodología

En cada punto analizado, se obtuvieron 3 espectros (3 beams) con 2048 valores (canales) cada uno, y un conjunto de datos relacionado a la concentración en ppm´s de cada elemento químico presente en el punto analizado. Estos datos pueden obtenerse como archivos de texto "csv" para su posterior tratamiento digital.

2. Materiales y metodología

Se utilizó un espectrómetro pXRF, DELTA Olympus, con detector de silicio SDD, tubo de r-X de Rh y en "Modo Suelo". Se realizó 3 disparos consecutivos en el mismo punto manteniendo la misma geometría. Las condiciones experimentales fueron:

beam-1: 15s, 40 KeV, 67 µA; beam-2: 20 s, 40 KeV, 34 µA; beam-3: 30s, 15 KeV, 78 µA.

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2. Materiales y metodología

Se verificó el funcionamiento del equipo usando la moneda de verificación de calibración (acero inoxidable 316). Siempre se usó la workstation y a través de la mini cámara CCD (modelo DP-600-CC) se observó el área irradiada (8 mm de diámetro). Los espectros y las concentraciones se obtuvieron utilizando el software Innov-X Delta.

2. Materiales y metodología

Se analizaron 7 billetes y 11 puntos por billete. Se obtuvieron 3 espectros por punto y 2048 datos por espectro, haciendo un total de (7*11*3*2048) 473088 datos. Sin embargo, el análisis preliminar mostró que el estudio podría realizarse solo con el tercer beam (espectro), disminuyendo significativamente la cantidad de datos a tan sólo 157696.

2. Materiales y metodología

Durante el experimento, los billetes se mezclaron de forma que no podían distinguirse los originales de los falsos. Se consideró que los resultados del pXRF podrían caracterizar e identificar los billetes originales, pues tendrían espectros similares, por provenir del mismo fabricante, mostrando correlaciones iguales a uno (cor (x, y) = 1).

2. Materiales y metodología

Con R-Studio v.0.99.486, se calculó la correlación de Pearson, que mide la relación lineal entre dos variables aleatorias cuantitativas. Se construyó una matriz de 2048 filas por 77 columnas (solo beam-3). El número de correlaciones para cada punto fue de 21=[7*(7-1)/2], haciendo un total de 231=(21x11) correlaciones (para los 11 puntos)

2. Materiales y metodología

En efecto, las correlaciones punto a punto entre billetes originales fueron iguales a 1, a pesar de ser usados y encontrarse en circulación. La presencia de algunos elementos reportada por el software Innov-X Delta tubo que ser evaluada y confirmada comparando los picos espectrales con las tablas de energía de emisión.

2. Materiales y metodología

Además, con la intención de demostrar la validez de nuestros resultados, utilizamos algunos estándares de suelos como el SRM® 2710a Montana I Soil y el SRM® 2711a Montana II Soil. Estos se colocaron en la workstation y se analizaron bajo las mismas condiciones que los billetes tanto originales como falsos.

Exploratory analysis for the identification of false banknotes using portable X-ray fluorescence spectrometer

2. Materiales y metodología

Con Pirouette 4.5, se realizó el análisis multivariado PCA. Se consideró 15 variables (elementos identificados por el software Innov-X Delta), y 77 muestras (conjuntos de datos de 11 puntos y 7 billetes). Un preprocesamiento de centrado medio fue realizado para mitigar la influencia de la magnitud del Ca y Ti, y se consideraron 7 factores como máximo.

3. Resultados y discusión

En billetes originales se identificaron 12 elementos : Ca, Ti, Cl, Zn, Cu, Fe, K, Sr, Mn, Zr, Cr y S (Tabla 1). Estos pueden separarse en tres grupos: el primero, con intensidades mayores (Ca y Ti), el segundo con intensidades medias (Cl, Zn, Cu, Fe y K), y el tercero con intensidades bajas (Sr, Mn, Zr, Cr y S). Además, se encontró Plomo en 2 de los 4 billetes originales.

Tabla 1. Promedio de intensidades del beam-3 en billetes originales

	Mayor intensities		Middle intensities				
Point	Ca	Ti	Cl	Zn	Cu	Fe	K
1	31360±3860	44375±926	4079±560	3800±152	2087±111	1941±261	1433±558
2	31728±5170	38686±689	3950±295	3845±218	2247±61	2086±238	1345±425
3	42480±7253	43742±1590	6072±427	3651±196	2124±151	2199±278	1117±258
4	51857±8260	38234±1491	3745±273	3633±93	2928±107	2149±239	1494±442
5	37424±5596	39448±1363	4437±237	3734±127	2397±106	1987±216	1174±383
6	36408±4866	39399±1579	4971±518	3665±49	2021±35	1724±191	1102±306
7	42836±8005	37371±568	4147±356	3669±154	2303±99	1915±304	1158±411
8	37394±6720	38130±1119	4502±226	3741±153	2301±91	2007±301	1209±426
9	36009±4332	37907±1298	4784±246	3646±69	2116±59	2034±473	1291±278
10	35404±4922	39064±543	4577±408	3704±144	2085±84	2057±409	1304±566
11	35552±5738	37578±2021	4429±510	3514±172	2240±120	1978±162	1312±462

	Lower intensities				
Point	Sr	Mn	Zr	Cr	S
1	702±25	362±8	206±8	142±18	120±13
2	722±26	400±33	215±3	139±9	157±29
3	681±21	419±68	216±11	136±22	147±14
4	716±35	594±173	224±2	140±13	188±8
5	719±33	431±72	225±1	147±5	145±7
6	686±35	346±16	202±5	127±12	127±13
7	687±16	442±83	203±4	137±7	145±10
8	717±41	395±39	205±5	131±16	141±9
9	736±16	379±16	199±15	133±10	136±9
10	695±12	398±60	214±3	132±16	130±20
11	661±31	415±62	199±20	132±7	125±17

3. Resultados y discusión

Estos resultados coinciden con los reportados por Appoloni y Melquiades (2014) destacando la presencia de Fe, Ti, Ca, Sr y Zr en billetes de 50 R/., Fe, Ti, Ca y Zn en billetes de 50$, y finalmente, la presencia de Ti, Ca e Y, en un billete de 50 €. Indicaron también la presencia del pigmento blanco de titanio en el papel moneda.

3. Resultados y discusión

En los billetes falsos (Tabla 2), se identificaron 15 elementos. Un primer grupo conformado por los mismos 12 elementos que en los originales: Ca, Cl, Ti, K, S, Fe, Mn, Zn, Sr, Cr, Cu y Zr, y otro, constituido por As, Y, Pb, donde As e Y aparecen una o dos veces, mientras que el Pb está en más de 7 de los 11 puntos analizados en todos los billetes falsos.

Tabla 2. Composición elemental (ppm) en billetes falsos

First Group- Same elements as in the original banknotes

Point		Ca	Cl	Ti	K	S	Fe	Mn	Zn	Sr	Cr	Cu	Zr
1	Bill I	145456±621	44980±292	27758±123	2308±43	1349±196	167±8	77±3	61±2	65±2	23±2	14±2	6±1
1	Bill III	183336±802	21836±205	62073±271	1752±44	1064±214	112±7	143±3	41±2	74±2	25±3	14±2	4±1
1	Bill V	158041±685	34009±256	54517±236	3736±54	1099±205	119±7	124±3	61±2	67±2	26±2	16±2	ND
2	Bill I	94194±414	160100±775	34911±152	6712±68	1693±224	286±9	56±2	45±2	66±2	11±2	13±2	5±1
2	Bill III	157636±677	89960±490	32816±145	789±34	2237±228	93±6	116±3	46±2	70±2	341±8	9±2	ND
2	Bill V	142999±610	82227±452	30035±132	2192±42	3018±226	135±7	106±3	87±2	70±2	663±6	13±2	ND
3	Bill I	120324±515	45916±295	28032±123	1819±45	811±181	155±8	96±3	62±2	61±2	22±2	9±2	8±1
3	Bill III	123737±519	15968±158	34552±147	1504±37	1290±175	134±7	127±3	54±2	69±2	26±2	14±2	ND
3	Bill V	142296±584	24609±195	29037±123	1831±38	1678±185	144±7	113±3	49±2	67±2	32±2	16±2	ND
4	Bill I	143139±595	36055±287	21837±97	1545±37	899±181	193±8	84±3	47±2	67±2	18±2	16±2	5±1
4	Bill III	172966±733	23229±198	33387±146	1081±36	931±196	134±7	192±3	45±2	76±2	21±2	14±2	ND
4	Bill V	160602±705	40082±275	32318±142	2690±47	1360±204	139±7	104±3	57±2	68±2	19±2	14±2	ND
5	Bill I	80330±378	211751±934	15583±70	794±28	1946±224	153±7	79±2	40±2	69±2	ND	11±2	8±1
5	Bill III	130943±548	46741±294	26724±116	1079±33	8274±256	214±9	366±4	45±2	73±2	14±2	10±2	ND
5	Bill V	137091±571	110642±554	26737±116	1664±37	1529±212	125±7	109±3	69±2	64±2	8±2	7±2	ND
6	Bill I	150489±628	36013±248	25606±112	1737±38	1181±188	171±8	87±3	75±2	69±2	24±2	9±2	6±1
6	Bill III	187094±795	22891±200	43078±187	1836±42	1216±207	104±7	122±3	48±2	78±2	28±2	9±2	ND
6	Bill V	167009±831	31813±252	40986±207	1880±45	1715±226	118±7	128±3	56±3	70±2	30±2	8±2	4±1
7	Bill I	170084±733	64692±362	34407±153	2623±47	1999±220	145±7	81±3	55±2	65±2	44±2	10±2	6±1
7	Bill III	153236±628	31531±241	37296±165	2166±45	1366±214	124±7	120±3	56±2	76±2	28±2	18±2	ND
7	Bill V	170862±727	41331±281	35323±155	3680±52	1795±212	146±7	108±3	64±2	88±2	36±2	23±2	ND
8	Bill I	153338±660	68476±399	25700±116	1122±36	1444±210	131±7	75±3	41±2	68±2	15±2	12±2	7±1
8	Bill III	162566±686	41575±278	32817±143	1034±35	5433±244	177±8	261±4	53±2	76±2	17±2	9±2	ND
8	Bill V	160215±670	63862±370	32058±139	3512±50	1661±210	130±7	99±3	66±2	67±2	15±2	14±2	ND
9	Bill I	155915±659	53264±328	29936±131	1478±38	1225±200	147±7	76±3	47±2	60±2	20±2	14±2	6±1
9	Bill III	195659±826	34570±252	38133±166	1577±43	1580±216	112±7	109±3	52±2	76±2	21±2	7±2	ND
9	Bill V	169972±716	35833±254	34325±149	2467±45	930±198	120±7	103±3	48±2	68±2	24±2	14±2	ND
10	Bill I	167759±716	50949±323	28627±128	1876±41	1379±208	159±8	78±3	56±2	71±2	24±2	7±2	9±1
10	Bill III	166097±715	60685±368	33807±150	1898±42	1897±219	120±7	125±3	53±2	77±2	21±2	13±2	ND
10	Bill V	134688±570	107414±549	31592±137	2891±48	1843±217	118±7	108±3	53±2	64±2	27±2	19±2	ND
11	Bill I	185394±772	18089±169	27564±121	1571±39	1005±195	165±7	91±3	98±3	77±2	26±2	12±2	9±1
11	Bill III	198976±845	24679±208	40205±175	1578±41	1699±215	98±7	120±3	56±2	78±2	29±2	7±2	ND
11	Bill V	163518±702	40428±280	42117±164	6200±62	1813±213	143±7	124±3	61±2	71±2	36±2	30±2	ND

Second Group- Elements (ppm) identified just once or twice but in different false banknotes

	Bill-I		Bill-III			Bill V	
Point	As	Pb	As	Y	Pb	As	Pb
1	ND	ND	ND	ND	ND	ND	ND
2	ND	6±1	6±1	ND	16±1	5±1	14±1
3	ND	ND	ND	ND	9±1	ND	13±1
4	ND	5±1	ND	567±10	7±1	ND	8±1
5	ND	6±1	ND	1157±18	5±1	ND	ND
6	ND	4±1	ND	ND	6±1	ND	7±1
7	6±1	12±1	ND	6±1	9±1	ND	10±1
8	ND	4±1	ND	650±11	4±1	ND	4±1
9	ND	4±1	ND	ND	6±1	ND	7±1
10	ND	5±1	ND	ND	9±1	4±1	11±1
11	ND	ND	3±1	ND	8±1	ND	12±1

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3. Resultados y discusión

La Tabla 3 muestra la correlación espectral entre billetes falsos (I, III y V) y originales (II, IV, VI y VII). Por ejemplo, en el segundo punto de análisis (2), la correlación entre el billete falso (I) y el original (II) es 0.81, mientras que la correlación, en el mismo punto, entre todos los billetes originales II-IV, II- VI, II-VII, IV-VI, IV-VII y VI-VII, es igual a 1.

Tabla 3. Correlacion espectral entre billetes originales y falsos

Banknotes Correlation	Analysis points										
	1	2	3	4	5	6	7	8	9	10	11
Bill I x II	0.97	0.81	0.99	1	0.67	0.97	1	0.98	0.99	0.98	0.93
Bill I x III	0.97	0.86	0.97	0.99	0.53	0.99	0.99	0.93	0.99	1	1
Bill I x IV	0.97	0.8	0.99	1	0.66	0.95	1	0.99	0.98	0.98	0.94
Bill I x V	0.98	0.86	0.98	1	0.87	0.99	1	1	0.99	0.92	0.98
Bill I x VI	0.96	0.75	0.99	0.99	0.64	0.98	1	0.99	0.99	0.98	0.96
Bill I x VII	0.95	0.77	0.99	1	0.69	0.96	0.99	0.99	0.98	0.97	0.93
Bill II x III	0.95	0.98	0.93	0.99	0.84	0.94	0.98	0.92	0.96	0.99	0.94
Bill II x IV	1	1	1	1	1	1	1	1	1	1	1
Bill II x V	0.98	0.98	0.94	1	0.95	0.95	0.99	0.99	0.97	0.95	0.98
Bill II x VI	0.99	1	1	1	1	1	1	1	1	1	1
Bill II x VII	1	1	1	1	1	1	1	1	1	1	1
Bill III x IV	0.95	0.97	0.95	0.99	0.83	0.93	0.98	0.93	0.95	0.99	0.96
Bill III x V	1	1	1	0.99	0.79	1	1	0.94	1	0.94	0.99
Bill III x VI	0.97	0.97	0.94	0.99	0.84	0.96	0.99	0.93	0.96	0.99	0.97
Bill III x VII	0.94	0.97	0.95	0.99	0.83	0.94	0.97	0.92	0.96	0.98	0.95
Bill IV x V	0.97	0.98	0.96	1	0.94	0.95	0.99	0.99	0.96	0.96	0.99
Bill IVx VI	0.99	1	1	1	1	1	1	1	1	1	1
Bill IV x VII	1	1	1	1	1	1	1	1	1	1	1
Bill Vx VI	0.98	0.97	0.95	1	0.93	0.97	1	0.99	0.97	0.94	0.99
Bill Vx VII	0.96	0.97	0.95	1	0.95	0.95	0.99	0.99	0.97	0.96	0.98
Bill VI x VII	0.99	1	1	1	1	1	0.99	1	1	1	1

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En la Figura 2a, se observa que las correlaciones entre billetes genuinos es 1, a excepción de IIxVI, IVxVI y VIxVII, en el punto 1. Esto podría deberse a la contaminación y desgaste de los billetes (VI) por estar en circulación. Esto muestra la reproducibilidad en la fabricación de los billetes, y al pXRF como una técnica potente en el análisis forense.

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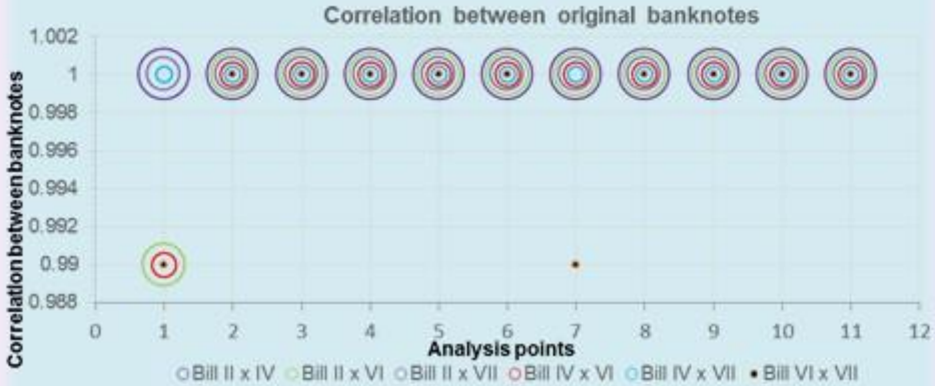
Figura 2a. Correlación espectral entre billetes originales (II, IV, VI and VII).



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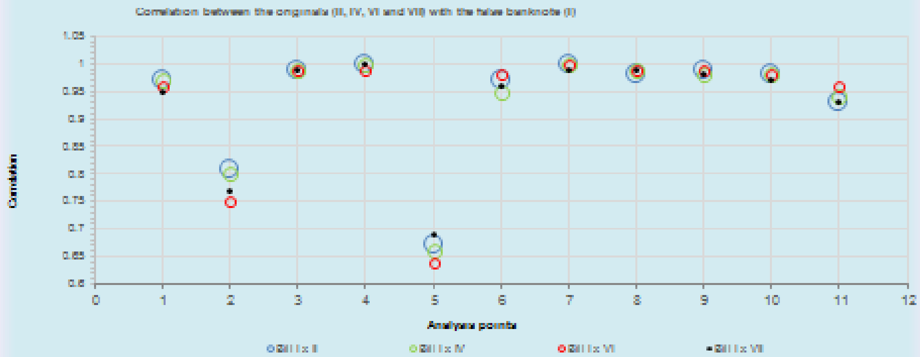
Se observó (Figura 2b) que las correlaciones entre los billetes falsos y todos los billetes originales en los puntos 4 y 7 son bastante altas, incluso dan 1. Esto nos permite concluir que dichos puntos pueden ser falsificados con facilidad (Fig. 2 - 1/3 "Billete Falso I")



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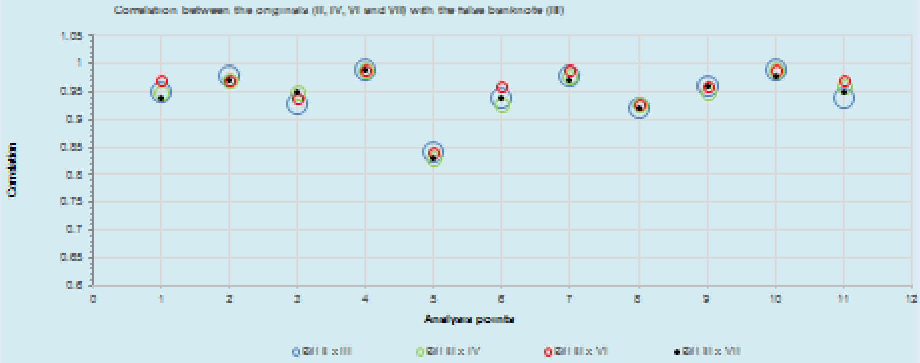
Se observó (Figura 2b) que las correlaciones entre los billetes falsos y todos los billetes originales en los puntos 4 y 7 son bastante altas, incluso dan 1. Esto nos permite concluir que dichos puntos pueden ser falsificados con facilidad (Fig. 2 - 2/3 "Billete Falso III")



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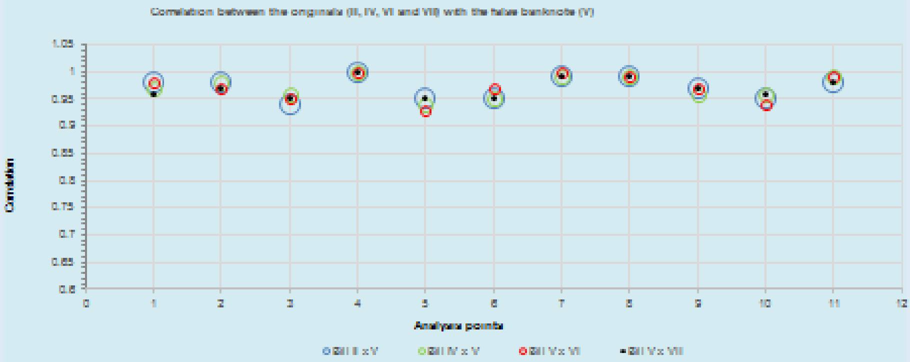
Se observó (Figura 2b) que las correlaciones entre los billetes falsos y todos los billetes originales en los puntos 4 y 7 son bastante altas, incluso dan 1. Esto nos permite concluir que dichos puntos pueden ser falsificados con facilidad (Fig. 2 - 3/3 "Billete Falso V")



Como las correlaciones entre billetes falsos y originales en los puntos 4 y 7 son altas, incluso algunos dan 1, podemos concluir que dichas marcas son falsificadas con facilidad

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De la Figura 2b, podemos concluir que la mejor falsificación corresponde al billete V (con correlaciones entre 0.93 y 1), y que el punto 5 es el más difícil de reproducir. Finalmente, diremos que el pXRF puede servir para desarrollar marcas de seguridad difíciles de falsificar.

3. Resultados y discusión

El resultado del análisis PCA (100% de la varianza acumulada), basado en la concentración obtenida por el pXRF, logra identificar dos grupos bien definidos: originales y falsos. Esto ratifica los resultados obtenidos por el análisis de correlaciones.

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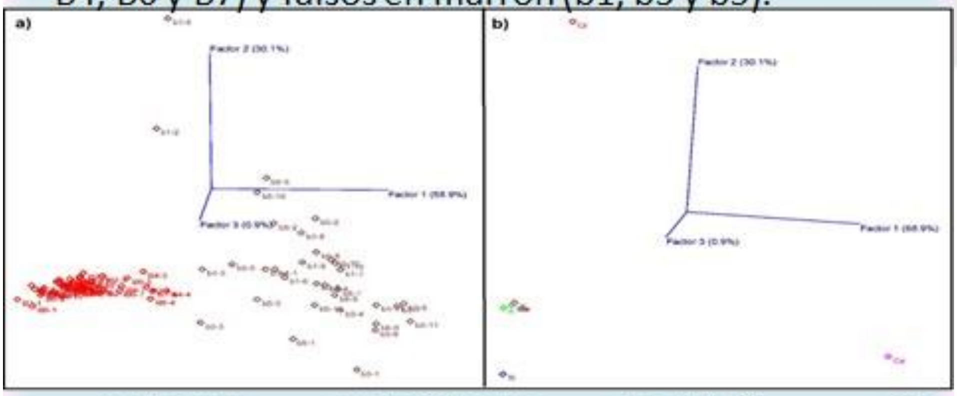
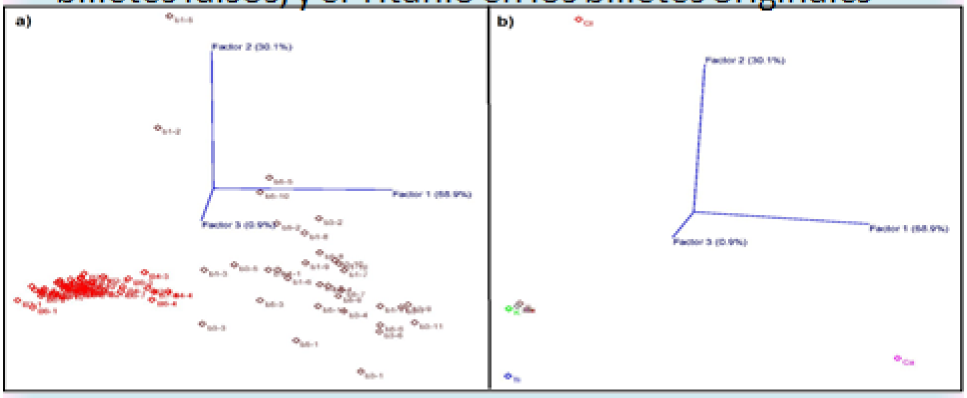
El gráfico 3D de "scores" (Figura 3a) muestra la separación en dos grupos: Originales en rojo (B2, B4, B6 y B7) y falsos en marrón (b1, b3 y b5).



El gráfico de “loadings” (Figura 3b) muestra que el Calcio es importante en la caracterización de billetes falsos, y el Titanio en los billetes originales



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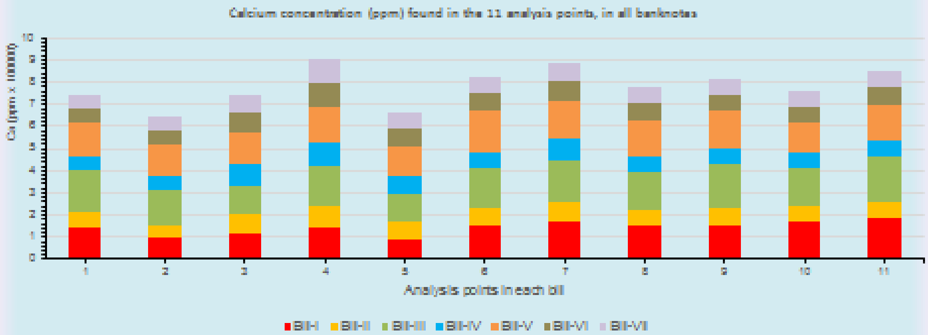
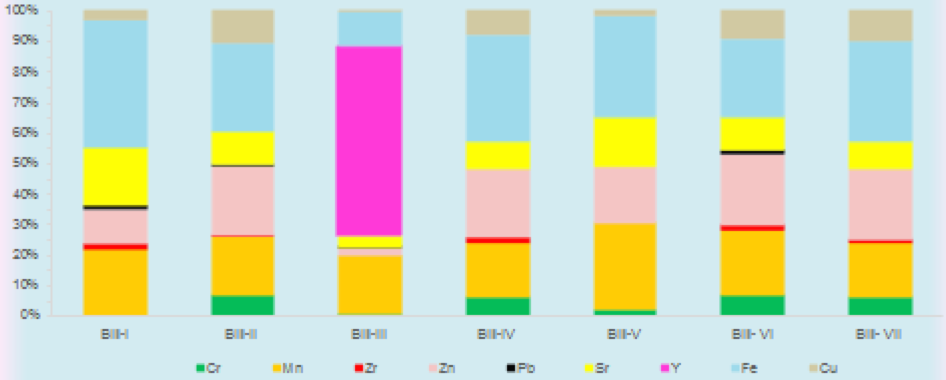
La presencia de Calcio en los billetes originales es notablemente menor que en los falsos. Esto se aprecia en la Figura 4.



La distribución de elementos traza (minoritarios) en el punto 5, se muestra en la Figura 5.



3. Resultados y discusión

Los resultados obtenidos por el pXRF de los Estándares SRM 2710a y SRM 2711a con sus valores certificados se comparan en la Tabla 4. Los valores del experimento corresponden al promedio de tres mediciones hechas bajo las mismas condiciones experimentales que para los puntos analizados en los billetes.

La Tabla 4 muestra que las concentraciones halladas por el pXRF son aproximadas a los valores certificados de los estándares.

Esto valida nuestros resultados obtenidos para los billetes de 200 soles.

SRM 2711a		
Element	Experimental (%)	Certified Values (%)
K	2.75 ± 0.02	2.53 ± 0.10
Ca	2.74 ± 0.02	2.42 ± 0.06
Ti	0.319 ± 0.030	0.317 ± 0.008
Fe	2.41 ± 0.02	2.82 ± 0.04
Element	Experimental (ppm)	Certified Values (ppm)
Cr	37 ± 3	52.3 ± 2.9
Mn	640 ± 6	675 ± 18
Cu	125 ± 4	140 ± 2
Zn	370 ± 6	414 ± 11
As	125 ± 8	107 ± 5
Sr	236 ± 5	242 ± 10
Y	35 ± 2	-
Zr	402 ± 8	-
Pb	1322 ± 11	-
SRM 2710a		
Element	Experimental (ppm)	Certified Values (ppm)
Sr	262±6	255 ± 7
Pb	5299±37	5520 ± 30

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3. Resultados y discusión

Finalmente, el pXRF nos permitió identificar la presencia de algunos elementos tóxicos en los billetes falsos, como: Cr, Pb y As. En el punto 2 de los billetes falsos Bill-III y Bill-V, el Cromo excedió bastante los límites permitidos por la Dirección General de Salud Ambiental-DIGESA en Perú (DIGESA, 2008). (Tabla 5)

3. Resultados y discusión

Table 5. Valores (ppm) de sustancias toxicas en billetes falsos (I, III and V)

		Cr		Pb		As
Maximum value		-	Bill-I:	12±1	Bill-I:	6±1
all studied banknotes	Bill-III:	341±4	Bill-III:	16 ±1	Bill-III:	6±1
	Bill-V:	663±6	Bill-V:	14±1	Bill-V:	5±1
Maximum limit allowed by DIGESA in toys		**60**		**90**		**25**

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4. Conclusiones

Los resultados del análisis elemental semi-cuantitativo utilizando el pXRF, ha demostrado que la composición química de la tinta utilizada en los billetes falsificados es diferente a la original.

El análisis de correlaciones de los espectros en RStudio permite reconocer el potencial del pXRF, como una técnica aplicable a la detección de billetes falsos de alta calidad.

4. Conclusiones

El pXRF permite también identificar las marcas de seguridad mas fáciles de reproducir por los falsificadores. El uso del análisis de componentes principales (PCA), en el procesamiento de datos, ratifica también la aplicabilidad del pXRF en este campo.

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Gracias . . . .