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Forensic Study on Chemical Stability of Indian Banknotes Using ATR-FTIR Spectroscopy

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Abstract

Background: Currency notes serve as the primary medium of financial transactions in India and are subjected to continuous handling and exposure to environmental factors such as moisture, heat, dust, oils, and other contaminants during circulation. These conditions may contribute to gradual chemical and physical alterations in the paper substrate of banknotes. Furthermore, the demonetization initiative implemented in 2016 resulted in the withdrawal and replacement of several denominations, significantly affecting circulation patterns, handling frequency, and the lifespan of Indian banknotes. Evaluating the chemical stability of circulated banknotes is therefore important from both forensic and material science perspectives.

Objective: This study aimed to investigate the occurrence of chemical degradation and compositional changes in Indian banknotes using Attenuated Total Reflectance–Fourier Transform Infrared (ATR-FTIR) spectroscopy.

Materials and Methods: A total of 32 Indian banknotes comprising 25 circulated and 7 fresh notes from five denominations (₹10, ₹50, ₹100, ₹200, and ₹500) were analysed. Five distinct regions of each banknote were selected to assess localised chemical changes resulting from circulation and environmental exposure. ATR-FTIR spectra were recorded in the mid-infrared region (4000–400 cm□¹). Characteristic absorption bands corresponding to O–H stretching (~3330 cm□¹), aliphatic C–H stretching (~2900 cm□¹), and cellulose fingerprint vibrations (~1427 cm□¹) were normalised against the glycosidic C–O/C–O–C band (~1050 cm□¹). Statistical evaluation was performed using the non-parametric Mann–Whitney U test in Microsoft Excel 2019.

Results: No statistically significant differences were observed in the normalised O–H and C–H ratios between fresh and circulated notes ($p > 0.05$). However, the cellulose fingerprint ratio (A1427/A1050) exhibited a moderate trend toward variation in circulated banknotes ($p = 0.092$). Region-wise analysis revealed localised significant differences in specific areas, likely due to surface contamination and moisture interaction rather than extensive chemical degradation.

Conclusion: The results showed the cellulose fingerprint ratio emerged as the most sensitive indicator of circulation-related changes, reflecting subtle cellulose degradation associated with frequent handling and use.

Keywords: currency notes, chemical degradation, ATR-FTIR, chemical stability, forensic examination

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Introduction

Currency notes primarily serve as a medium of exchange for goods and services in routine life across various sectors like hospitals, street markets, transportation, etc. During the process of manufacturing and frequent circulation, banknotes are commonly exposed to a variety of environmental, physical, and chemical stressors. It is because of their fibrous paper composition and extensive handling that banknotes can become potential carriers of environmental contaminants.[1]

Indian bank notes are primarily manufactured from high-quality cotton-based cellulose fibres, providing mechanical strength and durability while allowing the integration of multiple anti-counterfeiting security features. These include watermarks, windowed security threads, micro-printing, latent images, intaglio printing, optically variable and fluorescent inks, see-through register, and emblem printing.[2-4] Specialised magnetic and colour-shifting inks are incorporated to enhance the security features of a banknote. Despite these enhancements, the cellulose substrate, along with the chemical present in dyes, can be degraded by factors such as moisture uptake, thermal degradation, oxidative ageing, and chemical exposure from washing agents.[5] This leads to fibre degradation, ink instability, and reduced circulation lifespan

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of the banknotes.[6] Moreover, the cellulose present in the currency notes is often subject to be highly sensitive to certain environmental and chemical factors during manufacturing and circulation. Moisture can easily penetrate cellulose fibres, causing their hydrolysis and weakening the fibre structure, while environmental oxygen and humidity foster microbial and fungal activity that further degrade cellulose. Additionally, certain inorganic fillers, resin binders, and other security additives can interact with heat and chemical agents during usage and manufacturing, altering the durability of notes.[7,8]

Additionally, there are certain mechanical stresses, like repeated folding of a banknote, bending, and tearing degrade the banknote fibres, causing surface roughness and porosity, along with reducing stiffness.[9] Banknotes, during production and everyday circulation, are regularly exposed to various inorganic and organic substances capable of penetrating the paper's internal structure or the surface. For instance, the presence of fingerprints over time forms a thin layer of sebum on the banknote surface and causes a gradual deterioration and fading of printing inks.[10] Other factors like water, oxygen, and humidity may accelerate cellulose hydrolysis, oxidative ageing, and fungal growth, whereas low humidity causes dryness, reduced elasticity, and brittleness.[11]

Over the recent years, different spectroscopic techniques have been used for the examination of currency notes, such as infrared spectroscopy, near- infrared spectroscopy, Raman spectroscopy, and ATR-FTIR for a non-destructive analysis of banknotes. Several studies have reported the use of FTIR, IR, and microscope ATR-IR spectroscopy as a reliable method for differentiation of ink, paper substrates and distinguishing between genuine and counterfeit currency banknotes.[12-14] Studies have further stated that the usage of ATR-FTIR enhanced the surface analysis, enabling the effective characterisation of security inks, security threads, and other paper compositions, specifically when combined with the use of chemometric methods for profiling.[15,16]

While many studies demonstrate spectroscopic methods for the non-destructive examination of banknotes, most of the work is focused primarily on distinguishing between counterfeit and genuine banknotes. Although studies have shown results of characterisation of chemical profile over different regions on banknotes to identify the real and counterfeit currency using a portable NIR spectrometer coupled with chemometrics, a systematic and region-wise study on Indian currency notes, particularly using ATR-FTIR, remains unexplored.[17,18] Banknotes are not chemically homogeneous, and different regions such as security threads, inks, paper composition, and other security features on a banknote exhibit discrete chemical properties.[19] Each region has a difference in ink density, substrate, and exposure, which outlines that currency notes are chemically heterogeneous.[5] Therefore, region-wise spectroscopic examination of a banknote can provide characterisation of the localised chemical variation often caused by factors such as exposure to humid or dust-prone environments, regular handling, and circulation.

Additionally, events such as the demonetization (note ban) implemented in 2016 led to the withdrawal and replacement of certain denominations, significantly influencing the circulation patterns, lifespan, and handling frequency of Indian banknotes. Such large-scale monetary transitions may also affect the degree of wear, contamination, and potential chemical alterations in currency notes.

Accordingly, this widely utilised technique - ATR-FTIR spectroscopy is considered for assessing the characterisation of cellulosic materials, like cotton-based paper, and to evaluate its interaction with surface substrates like inks, oils, and environmental pollutants. ATR-FTIR spectra of cellulose and paper show a wide absorption in the 3300 to 3400 cm^{-1} range, which arises from O-H stretching of hydroxyl groups and water molecules that are adsorbed on the surface. These features reflect the strong hydrogen-bonding network and hydrophilic properties inherent to cellulose.[20-21] The absorption bands observed between 2800 to 3000 cm^{-1} are due to aliphatic C-H stretching vibrations, originating from $–CH_2$ and $–CH_3$ groups within the cellulose structure as well as from organic materials on the surface.[22] Within the fingerprint region 1420 to 1430 cm^{-1}, if the bands are recorded, then they correspond to CH_2 bending vibrations in cellulose. Meanwhile, the strong absorptions near 1050 cm^{-1} correspond with C-O and C-O-C stretching of β-1,4-glycosidic linkages, a key structural marker of cellulose.[20,23] These spectral traits, consistently reported in studies of cellulosic fibres, paper, and polymeric materials, provide a reliable means to examine both the core cellulose structure and surface chemical changes in aged or contaminated paper.

In view of this, the present study aims to use a non-destructive approach using ATR-FTIR to study the characterisation of the chemical composition of fresh and old Indian currency notes. The technique allows a distinctive examination of the deterioration of material over time, helps in verifying the authenticity of banknotes, and traces the handling history of currency. Despite the complex material composition of newly introduced currency notes, limited systematic research has been conducted on the physicochemical and structural characteristics of Indian currency notes. In contrast to this, several international studies have examined the compositional integrity, degradation behaviour, and durability of the currencies of their nations.[13,16,24] This present study aims to generate baseline spectral data for fresh notes and compare them with circulated notes for evaluating material degradation over time. Analysis of ATR-FTIR spectra allows identification of the possible effects on the structural properties of banknotes caused by the influence of environmental factors like humidity, dust, oil, etc., and regular circulation and handling can be evaluated. Such analysis not only assists in verifying authenticity and tracing handle history but also provides

information about the structural strength and robustness of Indian banknotes under varying conditions of usage.

Materials and Methods

Study Design

This study has been categorised as an observational analytical study of Indian currency notes using ATR-FTIR spectroscopy.

Place of the study

This study has been primarily conducted by the Department of Forensic Science, RIMT University, Punjab. ATR-FTIR examination was performed in the facilities of the Central Instrumentation Facilities (CIF), Lovely Professional University, Punjab, India. Statistical analysis and partial manuscript preparation were completed in the Department of Forensic Science, University Institute of Applied Health Sciences, Chandigarh University, Mohali, Punjab, India.

Time period

This study was carried out from September 2025 to February 2026.

Ethical Aspects

This study consists of the analysis of non-human samples (currency notes) and did not involve human participation; therefore, institutional ethical clearance was not required.

Sample size, collection, and classification

For the study, twenty-five circulated ("old") Indian banknotes and seven fresh ("fresh") Indian banknotes of ₹10, ₹50, ₹100, ₹200, and ₹500 were collected. Fresh bank notes were collected from the currency chest of the bank by making a request. All the banknotes were handled using clean gloves and stored individually in a paper envelope before any analysis to avoid additional contamination. These banknotes were further labelled individually as Note ID O1-O25 for the old, circulated banknotes, while F1, F2, F6, F11, F16, and F21 were for fresh banknotes, as shown in Table 1. Five distinct surface regions, namely, (A) denomination area, (B) Ashoka Emblem, (C) Printed area, (D) Non-printed backside, and (E) Security thread, were considered for analysis of each banknote [Figure 1-2].

Next, all the banknotes were categorised into different usage groups with respect to their visible surface conditions, such as crumpling, washing marks, oil stains, thermal exposure, or vendor-related handling. The classification category includes Washed, In-circulation, Oil, Vendor, and Heat-exposed currency notes. In certain cases, the selected banknotes were intentionally subjected to controlled treatments to simulate these conditions for comparative analysis. Before doing the ATR-FTIR analysis, old and fresh Indian Bank Notes were examined under a UV chamber that showed features like fading of fluorescent optical fibres, serial numbers not strongly

Figure 1: Front side of fresh Rs 500 Indian banknote depicting (A) Denominational area, (B) Ashoka Emblem, (E) Security thread

Figure 2: Back side of fresh Rs. 500 Indian banknotes depicting, (C) Printed area, (D) Non-printed area backside

Table 1: Details of currency notes used in this study

Note ID	Note Status	Usage Type	Year	Region Count	Serial Number	Note Denotation
O1	Old	Washed	2022	5	44P904622	10
O2	Old	In circulation	2018	5	89U934307	
O3	Old	Oil	2017	5	21C699278	
O4	Old	Vendor	2021	5	17D277814	
O5	Old	Heat	2023	5	57R237661	
O6	Old	Washed	2024	5	OAN200116	50
O7	Old	In circulation	2020	5	6FW021102	
O8	Old	Oil	2021	5	8KQ360503	
O9	Old	Vendor	2018	5	34D704423	
O10	Old	Heat	2024	5	8AP941669	
O11	Old	In circulation	2019	5	1DM484265	100
O12	Old	Washed	2024	5	ORL687625	
O13	Old	Oil	2023	5	2US706099	
O14	Old	Vendor	2022	5	8FH312215	
O15	Old	Heat	2022	4	8LD967780	
O16	Old	In circulation	2017	5	5BC903487	200
O17	Old	Washed	2019	5	ODT289233	
O18	Old	Oil	2019	5	OD7289233	
O19	Old	Vendor	2023	5	8FH829999	
O20	Old	Heat	2018	5	8FD389959	
O21	Old	In circulation	2018	5	5MW475909	500
O22	Old	Washed	2020	5	2W9495675	
O23	Old	Oil	2022	5	5H2480537	
O24	Old	Vendor	2017	5	99C551755	
O25	Old	Heat	2023	5	2RM968180	
F1	Fresh	NA	2025	5	93C917396	10
F2	Fresh	NA	2024	5	11U396929	
F6	Fresh	NA	2025	5	6UE918740	50
F7	Fresh	NA	2024	5	OU9096806	
F11	Fresh	NA	2025	5	2BQ520658	100
F16	Fresh	NA	2024	5	3PH069085	200
F21	Fresh	NA	2025	5	OBB446681	500

fluorescent and dark or faintly visible lines with minimal fluorescence of the security thread in old currency notes as compared to fresh currency notes. As a result, this forms the basis to proceed with the analysis of old and fresh Indian bank notes by ATR-FTIR spectroscopy.

Multiple regions for the analysis were chosen based on the previous FTIR studies that examined different banknote components, such as inks, coatings, and security threads, to obtain distinctive chemical properties of banknotes. The use of the ATR-FTIR technique is effective for analysing banknote inks and paper substrate materials.[13,16]

ATR-FTIR data acquisition

Spectra were recorded using an ATR accessory attached to an FT-IR spectrometer, PerkinElmer Spectrum IR version, following the standard instrument settings as provided by the central facility. For each region, one spectrum was taken across the mid-IR range (4000–400 $cm^{-1)}$ using the standard default

setting of the instrument for background, resolution, and scans (as listed in the instrument report). Each banknote sample was measured under the same contact pressure and instrumental settings to avoid inconsistencies. The CSV files produced by the instrument, showing absorbance versus wavenumber, were kept for numerical analysis.

ATR-FTIR is a non-destructive method used widely in forensic analysis for the differential examination of inks, polymers, and paper materials; quantitative analysis is based on numerical absorbance data exported by the instrument rather than on visual inspection of plotted spectra.[13,14,16,25-28]

Peak selection and chemical assignments

Four bands were selected based on the previous studies for identifying cellulose and common organic surface materials

- ~3330 cm^{-1} — The broad band around 3300–3340 cm^{-1} is assigned to O–H stretching from cellulose and moisture bound in the paper (hydrogen-bonded hydroxyls).[22,29]
- ~2900 cm^{-1} — Absorptions near 2900 cm^{-1} correspond to aliphatic C–H stretching (surface organics such as inks, binders, or oils) and are routinely used to assess handling/contamination on paper substrates[27,28,30]
- ~1427 cm^{-1} — The 1420–1430 cm^{-1} region (commonly cited at ~1427 cm^{-1}) is assigned to CH_2 bending modes of cellulose and is sensitive to changes in fibre order and mechanical/ageing effects.[30-32]
- ~1050 cm^{-1} — The 1050–1060 cm^{-1} glycosidic C–O/C–O–C stretching band is a well-established cellulose marker and is commonly used as an internal reference for normalisation of ATR-FTIR band intensities in paper/banknote studies.[28,30,33,34]

Data extraction, baseline handling, and normalisation

Peak absorbance values were taken from a CSV file produced by the instrument at the target wavenumbers or from the nearest point if the spectral peak shifted slightly. When a peak appeared weak as per observation or was not clearly visible in the plotted spectrum, the absorbance value at that corresponding wavenumber was still taken from the CSV file, because FTIR analysis is based on numerical measurements rather than visual interpretation of generated peaks. To normalise the data and minimise effects from variable contact or ATR sampling, the absorbance of each target band was divided by the absorbance of the ~1050 cm^{-1} glycosidic band from the same spectrum (i.e., the band was expressed as a ratio to A1050). Resulting normalised ratios were computed per region

$$\mathrm{ROH} = \frac{\mathrm{A3330}}{\mathrm{A1050}}$$

$$\mathrm{RCH} = \frac{\mathrm{A2900}}{\mathrm{A1050}}$$

$$\mathrm{RCell} = \frac{\mathrm{A1427}}{\mathrm{A1050}}$$

For each note, the five regional ratios were averaged to produce one note-wise mean for each ratio (Mean_R_OH, Mean_R_CH, Mean_R_Cell), and these note-wise means were used as the independent observations in all inferential statistics, as shown in Table 2.

Using an internal cellulose band (≈1050 cm^{-1}) as a reference within-spectrum is considered a standard approach for comparing relative band intensities in cellulose-containing materials because it provides a chemically relevant, stable reference arising from the glycosidic C-O/C-O-C vibrations.[22,35]

Statistical analysis

All inferential analyses were performed on note-wise mean-normalised ratios, such that each banknote contributed a single independent value for each parameter (Mean_R_OH, Mean_R_CH, and Mean_R_Cell), thereby avoiding pseudo-replication of region-level spectra.

Along with it, an exploratory region-wise analysis has also been performed to assess whether localised chemical variation exists across different banknote areas, shown in Figures 1 and 2. For this purpose, normalised ratios have been calculated from each analysed region (A-E), which were treated as independent observations and compared between old and fresh notes by means of the Mann-Whitney U test. This statistical analysis has allowed us to identify statistically significant variations in spectral characteristics due to circulation or environmental exposure. The same statistical analysis process described above has been applied to these region-wise datasets.

Mann–Whitney U test procedure

All observations from both groups were first combined and ranked in ascending order. In the presence of tied values, average ranks were assigned using Microsoft Excel 2019.

Let

- R_1 = Sum of ranks for old notes
- R_2 = sum of ranks for Fresh notes
- $n_{1=}$ number of old notes
- n_2 = number of fresh notes

The Mann–Whitney U statistics were calculated as

$$\mathrm{U}_1 = n_1 \times n_2 + \frac{n_1 \times (n_1+1)}{2} + R_1$$

$$U_2 = n_1 \times n_2 + \frac{n_2 \times (n_2+1)}{2} + R_2$$

The smaller value between U_1 and U_2 has been used as the test statistic (U) for testing the significance.

Normal approximation of U

For sample sizes exceeding 5 in at least one group, the sampling distribution of U was approximated by a normal distribution with mean and standard deviation μ_U and σ_U

$$\mu U = \frac{n_1 \times n_2}{2}$$

$$\sigma \mathrm{U} = \sqrt{\frac{n_1 \times n_2 \times (n_1+n_2+1)}{12}}$$

Table 2: Details of mean for each banknote sample

Note_ID	*Note Status*	*Usage Type*	*Note Denotation*	*Mean_R_OH*	*Mean_R_CH*	*Mean_R_Cell*
O1	Old	Washed	10	0.492	0.327	0.271
O2	Old	In circulation	10	0.428	0.305	0.229
O3	Old	Oil	10	0.405	0.489	0.346
O4	Old	Vendor	10	0.432	0.340	0.290
O5	Old	Heat	10	0.497	0.375	0.293
O6	Old	Washed	50	0.488	0.318	0.266
O7	Old	In circulation	50	0.504	0.388	0.289
O8	Old	Oil	50	0.492	0.548	0.330
O9	Old	Vendor	50	0.498	0.338	0.280
O10	Old	Heat	50	0.474	0.323	0.273
O11	Old	In circulation	100	0.444	0.489	0.666
O12	Old	Washed	100	0.452	0.504	0.717
O13	Old	Oil	100	0.545	0.804	0.524
O14	Old	Vendor	100	0.451	0.529	0.596
O15	Old	Heat	100	0.438	0.434	0.508
O16	Old	In circulation	200	0.419	0.527	0.447
O17	Old	Washed	200	0.416	0.512	0.434
O18	Old	Oil	200	0.477	0.864	0.400
O19	Old	Vendor	200	0.505	0.518	0.541
O20	Old	Heat	200	0.496	0.490	0.439
O21	Old	In circulation	500	0.404	0.489	0.454
O22	Old	Washed	500	0.463	0.384	0.331
O23	Old	Oil	500	0.436	0.786	0.597
O24	Old	Vendor	500	0.419	0.375	0.396
O25	Old	Heat	500	0.415	0.406	0.504
F1	Fresh	NA	10	0.494	0.361	0.269
F2	Fresh	NA	10	0.512	0.361	0.271
F6	Fresh	NA	50	0.557	0.407	0.329
F7	Fresh	NA	50	0.504	0.358	0.293
F11	Fresh	NA	100	0.457	0.348	0.332
F16	Fresh	NA	200	0.436	0.446	0.406
F21	Fresh	NA	500	0.411	0.435	0.322

A continuity correction of 0.5 was applied to improve the normal approximation for the discrete U distribution.

Standardised Z value has been calculated as

$$Z = \frac{U - \mu U \pm 0.5}{\sigma U}$$

Significance testing

The Z values calculated were used to determine two-tailed p values by referencing the standard normal distribution, and results were considered statistically significant at the significance level of $\alpha = 0.05$

Estimation of the effect size

The effect size has been calculated by using conventional

threshold values, where r ≈ 0.1 is considered a small effect, r ≈ 0.3 is considered a moderate effect, and r ≥ 0.5 is considered a large effect.

Effect size formula (rank-based):

$$r = \frac{|Z|}{\sqrt{N}}$$

Results

ATR-FTIR spectral features and normalisation

Representative ATR-FTIR spectra of Indian Currency Notes demonstrated apparent absorption bands corresponding to the cellulose-based substrate and associated surface constituents. Eminent features included a broad O—H stretching region (~3330 cm^{-1}), a C—H stretching region (~2900 cm^{-1}), the cellulose fingerprint region (~1427 cm^{-1}), and a strong glycosidic C—O/C—O—C stretching band near ~1050 cm^{-1}. To enable quantitative comparison across spectra obtained from different note regions and samples, absorbance values at 3330, 2900 and 1427 cm^{-1} were normalised to the corresponding absorbance at ~1050 cm^{-1}, yielding the ratios R_OH, R_CH and R_Cell, respectively. Note-wise mean values of these ratios were calculated by averaging measurements from the five analysed regions of each banknote.

Comparison of old and fresh banknotes

Normalised ATR-FTIR ratios were compared between old (n = 25) and fresh (n = 7) banknotes using the Mann–Whitney U test. Summary statistics and inferential outcomes have been shown in Table 3.

R_OH (3330/1050)

Mean_R_OH values showed substantial overlap between old and fresh notes. Mann-Whitney U Evaluation indicated no statistically substantial difference between the two groups: U = 62, Z = −1.140, p > 0.05. The equivalent effect size was small (r ≈ 0.20), indicating a nominal practical difference in the relative hydroxyl content of the cellulose substrate between dated and up-to-date banknotes.

R_CH (2900/1050)

For the normalised C—H stretching ratio (Mean_R_CH), old banknotes illustrated greater variability, especially among specimens placed under intensive handling and oil exposure. However, comparison with up-to-date banknotes showed no statistically significant discrepancy between the groups: U = 59, Z = −1.276, p > 0.05. The correlated effect size was small to moderate (r= 0.226), suggesting limited discriminatory separation between old and fresh notes when this parameter is assessed in isolation.

Table 3: Statistical summary of the outcomes

Normalized Ratio	*MW-U*	*Z value*	*p value*	*Effect size (r)*
R_OH	62	-1.140	0.254	0.202
R_CH	59	-1.276	0.202	0.226
R_Cell	50	-1.687	0.092	0.298

R_Cell (1427/1050)

The normalised cellulose fingerprint ratio (Mean_R_Cell) exhibited the greatest divergence between groups. Old banknotes generally showed higher ranks than fresh notes, reflected in a Mann–Whitney U value of 50 and a Z value of −1.69. Although this difference did not reach statistical significance of $p < 0.05$; ($p = 0.092$), the effect size was moderate (r ≈ 0.298), nearly 0.30, indicating a pronounced trend towards altered cellulose-related spectral characteristics in old banknotes.

Region-wise statistical comparison

To assess whether region-wise chemical variations are present across different areas of banknote surface, an additional region-wise statistical analysis has been performed, where normalised ATR-FTIR ratios obtained from each region were compared between old and fresh banknotes using the Mann-Whitney U test. The results of this analysis have been summarised in Table 4.

According to Table 4, most of the regions have not shown statistically significant variations between old and fresh bank notes due to a *p-value* > 0.05. However, some localised variations were observed in specific regions; for instance, in region B, the normalised C-H ratio (R_CH) has shown

Table 4: Summarised outcome of region-wise analysis of chemical variations on the surface of old and fresh bank notes.

Region	*Ratio*	*U value*	*Z*	*p-value*	*Effect size (r)*
A	R_OH	64	-1.048	0.294	0.185
	R_CH	64	-1.048	0.294	0.185
	R_Cell	82	-0.228	0.820	0.040
B	R_OH	77	-0.456	0.649	0.081
	R_CH	44	-1.960	0.050	0.347
	R_Cell	45	-1.915	0.056	0.338
C	R_OH	77	-0.456	0.649	0.081
	R_CH	52	-1.595	0.111	0.282
	R_Cell	59	-1.276	0.202	0.226
D	R_OH	40	-2.055	0.040	0.363
	R_CH	60	-1.110	0.267	0.196
	R_Cell	75	-0.402	0.688	0.071
E	R_OH	80	-0.319	0.750	0.056
	R_CH	69	-0.821	0.412	0.145
	R_Cell	56.5	-1.390	0.164	0.246

a statistically significant difference between old and fresh banknotes with U=44, Z= -1.960, and p ≈ 0.050. It has also shown a moderate effective size of r = 0.347. This finding suggests possible localised surface contamination or handling-related hydrocarbon deposition. Region D also exhibited a statistically significant difference for the hydroxyl ratio (R_OH) with U=40, Z= -2.055, p = 0.040, and a moderate effect size r= 0.363. It may reflect localised variation in moisture absorption or hydrogen-bonding characteristics of the cellulose substrate.

Discussion

The ATR-FTIR comparison presented in this study, between 25 circulated, old Indian currency notes and 7 uncirculated Indian currency notes, has shown a specific pattern that the hydroxyl-to-glycosidic ratio (R_OH, A3330/A1050) and aliphatic C-H-to-glycosidic ratio (R_CH, A2900/A1500) did not change between groups, as shown in Table 3 earlier. But, cellulose-fingerprint ratio (R_Cell, A1427/A1050) has highlighted the strongest separation, shown in Table 3, which is a trend-level result with a moderate effect size. In a consolidated way, results have indicated that bulk hydroxyl character and overall surface organics (including inks and print binders) remain comparable among fresh and old notes, while subtle structural alteration within the cellulose matrix can be a sensitive indicator of ageing or usage, as shown in this dataset.

ATR-FTIR is widely used to monitor molecular changes in cellulose and paper because the technique readily captures carbohydrate (C–O/C–O–C), hydroxyl and C–H vibrational bands; prior studies have shown that ageing (natural or accelerated) alters band intensities in these regions. In accordance with the findings of the study, R_Cell has shown the strongest trend towards differentiation between circulated and uncirculated notes, which clearly aligns with previous works, which have shown that fingerprint region characteristics (glycosidic and ring vibrations) are responsible for cellulose chain-breakage and oxidation. [36,37]

But ATR-FTIR is surface-sensitive (sample penetration depth is small), so spectral changes from surface-adsorbed contaminants (skin oils, hydrocarbons, printing residues) can increase variability—especially in the C–H region—masking or diluting bulk-cellulose signals. In this study, higher variability for R_CH among old notes is consistent with surface contamination effects, which have also been reported in other previous studies.[27,38]

Previous controlled ageing studies have shown changes in OH and carbonyl absorption occur as the materials go through hydrolysis or oxidation, but the direction and magnitude depend strongly upon ageing conditions like temperature, humidity and pollutants and sample history. In this study, the R_OH difference is small and insignificant, which reflects the heterogeneous, real-world ageing of circulated currency rather than controlled laboratory ageing. This justifies the conclusions from previous reviews and experimental ageing papers that caution against expecting neat, large-amplitude OH shifts in samples aged naturally and mixed-history samples.[39,40]

The C–H stretching region is often a sensitive marker for hydrocarbons from skin oils, lotions, or environmental deposition. The data reported in this study have shown elevated variability for older notes and no significant group difference, which fits previous reports where increased C–H signal is associated with adsorbed organics on the paper surface rather than intrinsic cellulose chemistry. Therefore, it supports interpreting R_CH variability as a contamination/handling signature rather than an ageing marker.[27,38]

The moderate effect size and nearly statistically significant (p = 0.092) for R_Cell has highlighted that repeated circulation fastens measurable alteration of the fingerprint bands (1427 cm^{-1} relative to 1050 cm^{-1}). This phenomenon is consistent with studies linking the fingerprint region with glycosidic bond integrity and with oxidation/hydrolytic changes in cellulose (manifested as shifted or intensity-changed bands). In controlled ageing experiments, fingerprint changes are one of the more reproducible indicators of polymer backbone modification.[36,41-44] In this study, with a modest sample size of fresh notes (n = 7) and the heterogeneous nature of old notes, the trend in the data appears scientifically plausible and matches literature expectations.[36-37]

The region-wise ATR-FTIR evaluation implemented in this study demonstrates that maximum banknote regions did not indicate statistically significant deviation between circulated and fresh samples. However, localised differences have been observed in specific regions, specifically in the C–H stretching band in Region B and the O–H stretching band in Region D. Such variations are uniform with the heterogeneous behaviour generally observed in cellulose-based materials and paper substrates during environmental ageing and recurring handling. Prior infrared spectroscopic investigations have corroborated that cellulose-containing materials often exhibit variability in vibrational bands contingent upon localised exposure to environmental stimuli, including moisture, surface oils, and mechanical wear. Specifically, ATR-FTIR studies of aged paper materials have shown that the broad O–H stretching region (3000–3600 cm^{-1}) is highly sensitive to changes in hydrogen-bonding interactions and moisture absorption within cellulose fibres, which can generate localised fluctuations in spectral intensity due to ageing or environmental exposure.[36,39]

The aliphatic C–H stretching region (2800–3000 cm^{-1}) is generally associated with surface organic materials such as oils, binders, and other environmental adulterants accreted during handling. Variance in this spectral region has been broadly reported in studies examining paper substrates and cellulose-based materials subjected to environmental exposure or human contact. In the case of circulated banknotes, repeated handling can incorporate sebum residues, hydrocarbons, and other organic contaminants onto the paper surface. These materials induce additional C–H vibrational signals, which may amplify spectral variability without necessarily indicating structural degradation of the intrinsic cellulose matrix.[30]

In addition, ATR-FTIR experiments of ageing processes in

cellulose-derived and polymeric materials have corroborated that degradation can occur heterogeneously across different regions of the same sample. Differential exposure to environmental factors such as light, humidity, and mechanical stress may generate localised degradation gradients, resulting in region-specific chemical changes observable at certain sampling points but not evenly throughout the material.[44]

Subsequently, the limited number of region-specific statistically consequential differences observed in the present study likely reflects localised surface interactions rather than comprehensive chemical degradation of the banknote substrate. The overall deficit of widespread spectral differences across most regions corroborates the analysis that the cellulose matrix of Indian banknotes remains chemically stable irrespective of routine circulation and handling. This observation is consistent with prior research indicating that cellulose-based paper materials are generally subjected to slow structural degradation under natural environmental conditions, with most spectral variations emerging from surface contamination, moisture interactions, or localised mechanical stress rather than bulk chemical breakdown of the polymeric cellulose backbone.[45]

Practical and forensic implications

For authenticity *vs* ageing: FTIR/ATR has proven useful in distinguishing material composition differences (used *vs.* counterfeit banknotes) and for profiling inks/security elements when combined with chemometrics. The findings of this study have suggested that simple univariate normalised ratios are not strongly discriminatory between old and fresh notes under real-world heterogeneity, but the R_Cell trend implies that multivariate approaches could enhance discrimination.[14-46]

For forensic trace analysis, banknotes are also useful matrices for detecting external residues (explosive residues, drugs, oils). Surface contamination signatures observed in the C–H region reinforce that the top surface is informative for contact/transferred materials.[47]

Limitations of this study

ATR-FTIR is sensitive to surface characteristics; the spectral differences observed could be affected by surface contamination. Techniques that can examine the depth profile of a sample, such as transmission FTIR of cross-sectioned samples or μ-FTIR imaging, may give possible accuracy in the differentiation of surface effects and bulk cellulose degradation.[44] Artificial ageing influenced by controlled humidity, temperature, and exposure to environmental pollutants on the selected banknote paper surface can help connect specific degradation processes like oxidation, hydrolysis, and soiling to changes observed in spectra.[37,39] Further, using advanced data analysis methods such as multivariate chemometrics can help in detecting minute differences in the spectra of a banknote that can allow a clear identification of the handling history and circulation of the banknote.[46-48]

Conclusion

In this study, ATR-FTIR spectroscopy was used to examine fresh and circulated Indian banknotes in accordance with their handling, exposure to environmental factors like humidity, moisture, dust, etc., and regular usage. The results showed that the hydroxyl- and C-H- based ratios were largely similar for both groups of circulated and uncirculated notes, indicating that general paper chemistry and surface contaminants do not change their regular use consistently. However, the cellulose fingerprint ratio was shown to be the most sensitive marker for identifying changes in cellulose degradation caused by circulation and frequent handling of banknotes.

The obtained results may also reflect the presence of robust security features, inorganic fillers, and engineered substrate materials in Indian banknotes, which are designed to withstand chemical and mechanical stress even during circulation. It was further noted that ATR-FTIR techniques can aid in forensic analysis by detecting circulation-related structural changes in banknotes, particularly focusing on the R_Cell region, and identifying surface contaminants. However, its surface sensitivity limits detection of bulk cellulose degradation, and variability from handling or environmental exposure may affect results, indicating the need for the application of multivariate analysis for more accurate results with respect to distinct handling history and circulation of Indian banknotes.

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