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International Journal of Forensic Sciences
ISSN: 2573-1734

Forensic Characterization of Nacre (Mother of Pearl) by pXRF and DRIFTS Analysis

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Research Article
Volume 10 Issue 3
Received Date: September 04, 2025
Published Date: September 29, 2025
DOI: 10.23880/ijfsc-16000447

Abstract

This study aimed to develop non-destructive methodology to distinguish natural nacre (Mother of Pearl) from synthetic imitations, a task of growing importance due to increased demand and illegal trade. The research employed two key analytical techniques: portable X-ray fluorescence (pXRF) and diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS). Natural mollusk shells (n=50) and commercial synthetic Mother of Pearl products (n=18) were analyzed. The pXRF results revealed that natural nacre and crafted nacre – composite materials containing synthetic and natural nacre parts – had higher relative concentrations of calcium (Ca) and strontium (Sr), with a distinct Ca/Sr ratio. In contrast, artificial samples lacked these elements and had a higher percentage of light elements (LE), indicating an organic, polymer-based composition. DRIFTS analysis characterized the molecular structure. Natural nacre spectra consistently showed peaks characteristic of aragonite, a crystalline form of calcium carbonate. While the synthetic samples, including the crafted nacre composites, displayed spectra consistent with polymers like epoxy resin and acrylic.

The findings confirmed that a combination of visual inspection for iridescence, pXRF elemental analysis, and DRIFTS analysis provides a robust approach for differentiating natural nacre from synthetic look-alikes. This method can assist in monitoring and combating the illegal trade of mollusk shells.

Keywords: Nacre; Forensic; pXRF, Drifts; Iridescence; Mother of Pearl

Abbreviations

pXRF: Portable X-Ray Fluorescence; DRIFTS: Diffuse Reflectance Infrared Fourier Transform Spectroscopy; LE: Light Elements; MOP: Mother of Pearl.

Introduction

Nacre, found in some species of mollusks, is the colorful naturally occurring substance containing both inorganic and organic components. Also known as Mother of Pearl (MOP), this complex material is comprised of 95% by weight of the inorganic mineral calcium carbonate and displays a variety of iridescent colors, making nacre desirable and valuable [1]. Nacre is commonly used in jewelry, buttons, and as inlays in various items, from wooden string instruments to knife handles [2].

Iridescence in Nacre

Nacre's iridescent, color-changing appearance is a form of structural coloration caused by the interaction of light with a mollusks unique layered structure of protein and calcium carbonate; this is an example of diffraction and thin-film interference, similar to soap bubbles or oil slicks [1,3,4]. The iridescent, rainbow-like colors of nacre also appear to separate into their constituent spectral components on close visual evaluation, a phenomenon that could be attributed to dispersion [5]. Sun J, et al. [6] reviewed the development of the carbonate crystal layers and Madhav D, et. al. [1] discussed how incident light interacts with the structure of nacre to display the color shifts generated by the surface. Individual calcium carbonate crystals act as "bricks" that are held together by an organic matrix "mortar" that accounts for the remaining 5 wt.% of the shell and includes components such as polysaccharides and glycoproteins [7].

The hierarchical architecture of nacre is complex with varying spacing, crystal thickness, and orientation of the grooves and indentations of the crystal carbonate structure creating grating; this grating interacts with light resulting in the multi-color luster typical of nacre [1,3,4,6]. We observed this intricate crystalline structure that is characteristic of nacre in a *Pteria* sp. (winged oyster) shell using a Phenom XL Desktop Scanning Electron Microscope (Nanoscience Instruments, Inc., Phoenix, AZ, USA) (Figure 1).

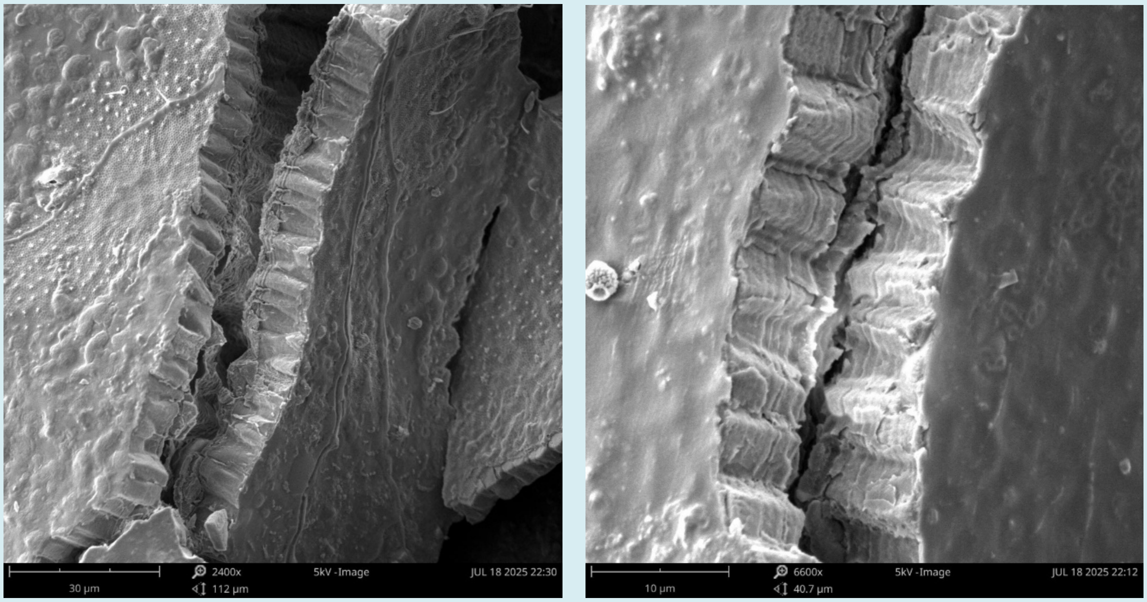

Figure 1: Scanning electron microscope (SEM) images of *Pteria* sp. (winged oyster) demonstrated the intricateness of the calcium carbonate crystal platelets held together by an organic matrix consisting of various molecules, including proteins, at 30 microns (A) and 10 microns (B).

Visually the nacre layer disperses the light causing an iridescent glow or luminosity. Tan TL, et. al. [3] and Liu Y, et. al. [4] have described this phenomenon in abalone and pearl oyster shells where a crystal grating, produced by the calcium carbonate, creates structural rainbow-like colors from the interaction with incident light. Synthetically manufactured Mother of Pearl look-alike materials often reflect the incident light to produce a shiny effect (e.g., glitter), but this phenomenon is based on refraction and reflection of light [8]. Other manufactured materials use polymers which display iridescence by employing thinly grated surface features that successfully create structural color, mimicking MOP iridescence. However, these polymers do not contain calcium carbonate [8-11]. Although some iridescent imitations can be transparent and film-like, pigments, shimmery flakes, and stains have frequently been observed to also be incorporated in the synthetic material [8,10,11]. Some manufacturers indicated that nacre, or MOP, products could be synthesized by taking small flakes of natural nacre and mixing them with either acrylic or glue to produce thin sheets or scales [12,13], this approach produces a substance we refer to herein as "crafted nacre".

Nacre in Trade

Limited research conducted by Chand S, et. al. [2] between 2010 and 2013, to study tourist purchasing habits in Fiji, estimated that MOP shell products contributed approximately 2.73 million USD to the local community [14]. Commercial online marketplaces such as Amazon® and Etsy© that sell natural MOP products and inlay materials do not always list the species name [15,16]. This could affect the ability to successfully monitor trade and can lead importers and exporters to circumvent applicable tariffs.

Government agencies monitoring artisanal fishing activities, such as the harvesting of nacre products, are nearly non-existent. There is also evidence of under-declaring export volumes, as well as unreported and illegal trade [17,18]. Accurate monitoring of species in trade ensures population stability for ecosystem viability, recreational use, and commercial fishing demands. An example of overfishing of pinto abalone occurred in Washington state from 1980 to 1992, and although commercial fishing was never permitted, local authorities authorized recreational harvesting through "daily take" and size limits [19]. An estimated 40,000 abalone were harvested yearly from combined recreational and illegal fishing; however, a single poacher admitted to taking upwards of 40,000 abalones to sell to restaurants, locally and overseas, mainly from pinto abalone herds during spawning season [19,20]. This kind of behavior drastically reduced the population to near extinction [19,20].

Employing a non-destructive analytical technique such as portable x-ray fluorescence spectrometry (pXRF) is useful in determining natural nacre. The portable XRF offers the ability for elemental analysis to be conducted in situ as well as the capability to analyze larger items that cannot fit into the chamber of typical micro-XRF systems like the EDAX, Orbis (AMETEK, Inc., Pleasanton, CA, USA) [21]. The objective of this study was to assess the ability of a portable XRF system to differentiate natural nacre from synthetic or imitation Mother of Pearl products employing elemental analysis. Additionally, we examined MOP and synthetic materials using diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) which allows for the identification of synthetic polymers used in look-alike MOP items.

Materials and Method

Reference Materials and Samples

Natural mollusk shells (n=50), including samples of *Haliotis* spp. (abalone), *Pteria* spp. (winged oyster), and *Pinctada* spp. (oyster), that displayed natural nacre were analyzed. The shells were from multiple geographic locations including Mexico, Australia, the Philippines, and the United States of America (Table 1).

Species	Number of Specimens	Geographic Source	Common Name
Haliotis corrugata	5	California, United States	Pink abalone
Haliotis corrugata	2	Ensenada, Mexico	Pink abalone
Haliotis corrugata	1	N/A	Pink abalone
Haliotis cracherodii	1	California, United States	Black abalone
Haliotis fulgens	1	Ensenada, Mexico	Green abalone
Haliotis kamtschatkana	1	Alaska, United States	Pinto abalone
Haliotis kamtschatkana	2	California, United States	Pinto abalone
Haliotis ovina	1	Philippines	Sheep's ear abalone
Haliotis rubra	2	Sydney, Australia	Blacklip abalone
Haliotis rufescens	8	California, United States	Red abalone
Haliotis rufescens	4	N/A	Red abalone
Haliotis sp.	4	N/A	Abalone
Haliotis wallalensis	2	California, United States	Flat abalone
Isognomon isognomon	2	Queensland, Australia	Wader tree oyster
Malleus albus	1	Cebu, Philippines	White hammer oyster
Pinctada mazatlantica	1	Baja California Sur, Mexico	Pearl oyster
Pinctada mazatlantica	3	Guaymas, Mexico	Pearl oyster
Pteria sterna	1	Baja California Sur, Mexico	Pacific winged oyster

Pteria sterna	4	La Paz, Mexico	Pacific winged oyster
Pteria sterna	1	Puerto Vallerta, Mexico	Pacific winged oyster
Pteria tarentina	2	Philippines, Samar	Winged oyster
Pteria sp.	1	Manila Bay, Philippines	Oyster

Table 1: Summary of natural nacre shell specimens tested and their geographical origins.

Elephant ivory specimens (n=11), *Loxodonta* spp. & *Elephas maximus*, and walrus ivory specimens (n=12), *Odobenus rosmarus*, were chosen to be used as controls for determining the daily accuracy of the pXRF because of their high calcium content [22,23] and the ease with which the pXRF can detect this element. All shells and ivory are housed in the U.S. National Fish & Wildlife Forensic Laboratory (Ashland, OR) morphology collection. Synthetic MOP samples (n=18) and crafted nacre samples (n=2) were obtained from commercial sources and are summarized in Table 2 and Figure 2. Other artificial specimens were claimed by the manufacturer to be made of materials ranging from acrylic (polymethyl methacrylate or PMMA) to paint or adhesive (Table 2 and Figure 2).

Specimen Description	Source	Claimed to Contain	Iridescence?	Reference
Acrylic blank craft sheets	Delvie's Plastic, Maker Stock, Etsy	Polymethyl methacrylate (acrylic)	Absent	[24]-[26]
Acrylic craft paint	Craft store	Titanium dioxide, Talc	Absent	[27]
Guitar pick	Amazon®	Celluloid	Absent	[28]
Crafted nacre, scale slab inlays	Amazon®	Natural nacre, acrylic, glue	Present	[12]-[13]
Nail lacquer	Drug store	Nitrocellulose	Absent	[29]-[31]
Sticker adhesive veneer imitation abalone	Amazon®	Not declared	Absent	[32]-[33]
Plastic hair clip	Amazon®	Not declared	Absent	[34]

Table 2: Summary of commercial synthetic specimens tested and their results after visual inspection confirmation for iridescence.

Figure 2: Various samples of crafted nacre (a composite of natural nacre parts with organic polymer-based materials) and artificial imitations of nacre that were tested.

Visual Inspection for Iridescence

The presence of iridescence was determined by visual inspection via Video Spectral Comparator (VSC) 8000/HS (Foster + Freeman Ltd., Evesham, Worcestershire, UK), utilizing a flood light and with a polarizing filter.

Portable XRF

Analysis of all samples listed in Table 1 and Table 2 were performed using a SciAps X-50 portable pXRF (SciAps Inc., Andover, MA, USA) featuring a Silicon Diode detector (SDD detector). Data was collected using Mining mode for quantitative determination of elemental composition using the following acquisition settings: exposure time of 30 seconds, the x-ray voltage set to 40 KeV and the current set to 32.4 µA. The diameter of the pXRF aperture is approximately 7mm. A set of five measurements per sample were collected from different locations, the flattest area of the sample surface was utilized for each measurement. No mechanical or solvent cleaning was performed on any of the samples prior to analysis.

Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) Analysis

Natural nacre shell specimens (n=5) and all the commercial synthetic specimens listed in Table 2 were analyzed using DRIFTS following the procedure described by Espinoza EO, et. al. [35] employing the Nicolet Nexus Smart Collector™ sample holder of the Nicolet iS50 FTIR (OMNIC v.9 software, Thermo Fisher Scientific Inc., Madison, WI, USA). Each DRIFTS spectrum collected consisted of 80 scans at a resolution of 4 nm that resulted in data spacing of 0.482 cm^{-1} with autogain, the 80 scans from one location were averaged to create each spectrum. Each item was sampled by sanding with 320 grit silicon carbide collection discs. The DRIFTS spectra of the commercial synthetic specimens were identified using a spectral match against a commercial polymer library and an in-house wildlife library containing appropriate refence spectra using OMNIC version 9 software (Thermo Fisher Scientific Inc., Madison, WI, USA).

Results

Presence of Iridescence

Visual examination revealed the presence or absence of iridescence (Table 2). Iridescence was observed as a rainbow-like gradient that had a lustrous, luminosity (Figure 3A). In contrast, especially under polarized light, items that did not have iridescence were perceived as appearing dull and were nearly colorless (Figure 3B). Some items contained reflective or shimmery flakes in an attempt to mimic an iridescence from a distance, but they lacked the structural coloration in the form of rainbow-like colors that occur in natural nacre.

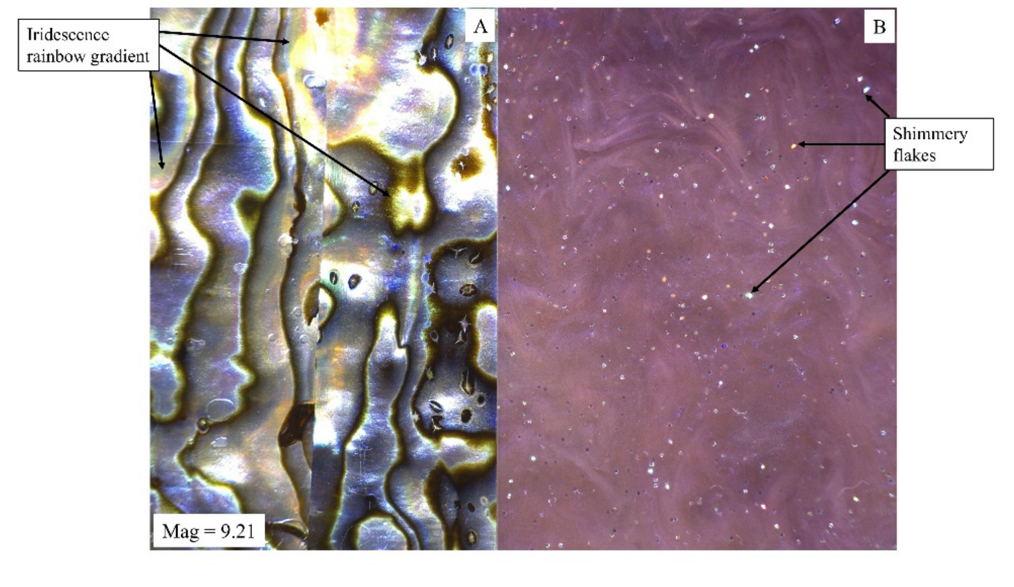

Figure 3: Video Spectral Comparator (VSC) image taken with a polarized filter of a crafted nacre sample (composite of natural nacre scales with glue) (A) that observed iridescence present compared to an artificial imitation sample of nacre (acrylic blank craft sheet) (B) that lacked iridescence and instead contained shimmery flakes.

Portable XRF Analysis

Portable XRF (pXRF) elemental analysis of the samples is summarized in Table 3. The natural nacre shell samples, and the two composite crafted nacre samples revealed higher relative concentrations of calcium (Ca) and strontium (Sr), and the results are shown graphically in Figure 4 and Figure 5. Giliken DP, et al. [36] showed that Ca/Sr ratios are strong indicators of biological control in marine aragonitic shells, and we have estimated these ratios for the samples analyzed. The calculated ratio of all the samples in this set is shown in Figure 6.

Specimen	Number of Specimens	LE (%)	Calcium (%)	Strontium (%)	Calcium to Strontium Ratio (%)	Other Elements Detected
Acrylic	6	96.56 - 99.22	None Detected	None Detected	None Detected	Titanium, lead
Acrylic paint	2	55.89 - 76.32	31.17 - 42.57	None Detected	None Detected	Titanium
Celluloid	1	87.12 - 87.49	None Detected	None Detected	None Detected	Iron
Nail lacquer	3	91.78 - 95.79	None Detected	None Detected	None Detected	Titanium, manganese
Crafted nacre	2	26.83 - 50.06	49.67 - 71.93	0.09 - 0.32	0.02 - 0.08	None Detected
Natural nacre	50	9.80 - 55.37	44.57 - 89.92	0.06 – 0.47	0.02 - 0.08	None Detected
Sticker adhesive	3	72.76 - 86.47	None Detected	None Detected	None Detected	Titanium, zinc
Plastic hair clip	1	99.45 - 99.72	None Detected	None Detected	None Detected	None Detected

Table 3: Elemental results by pXRF for natural nacre and synthetic specimens.

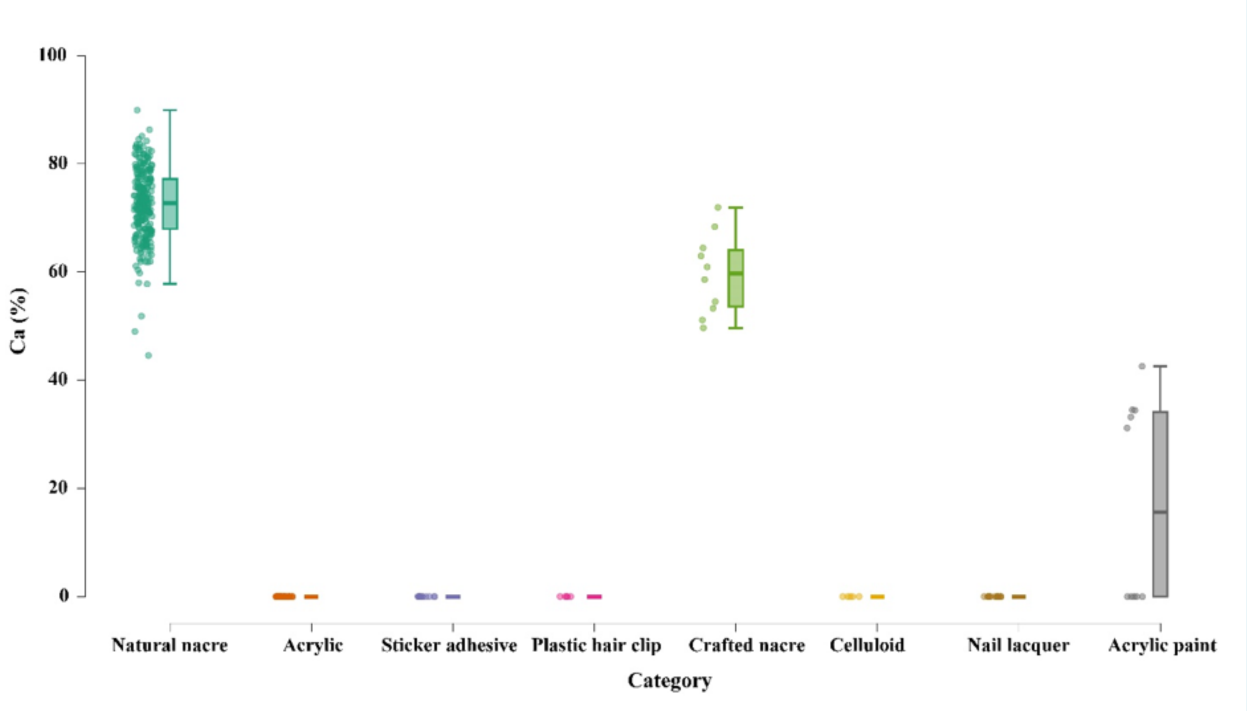

Figure 4: Relative concentrations (%) of calcium of various specimens measured by pXRF.

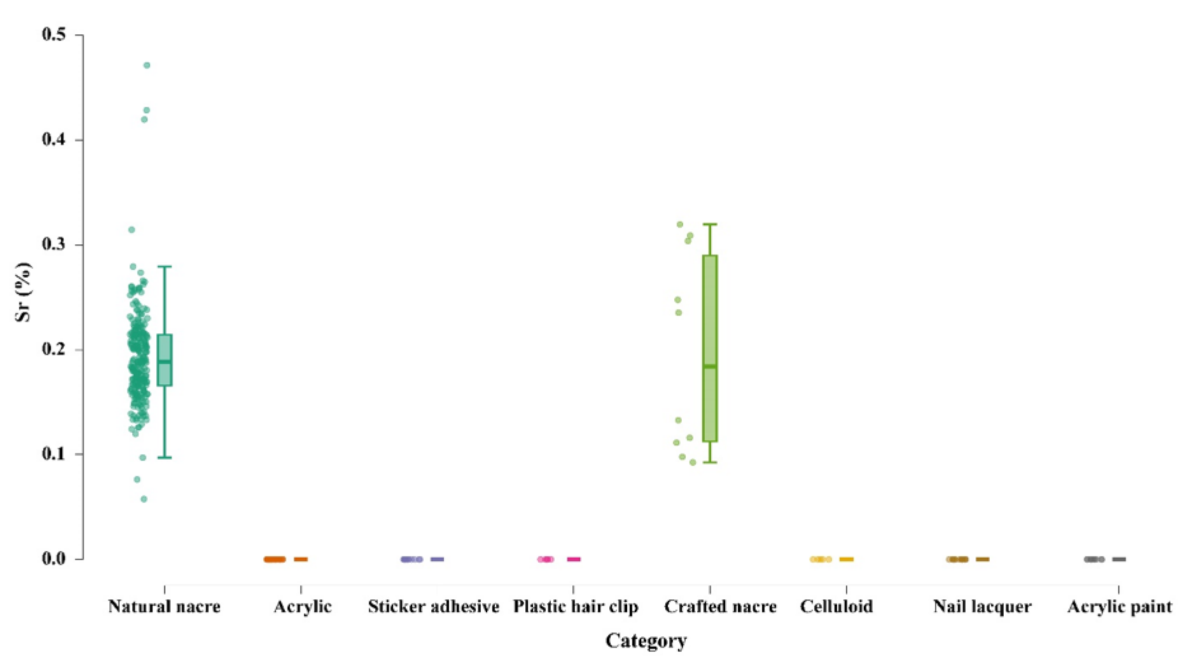

Figure 5: Relative concentrations (%) of strontium of various specimens measured by pXRF.

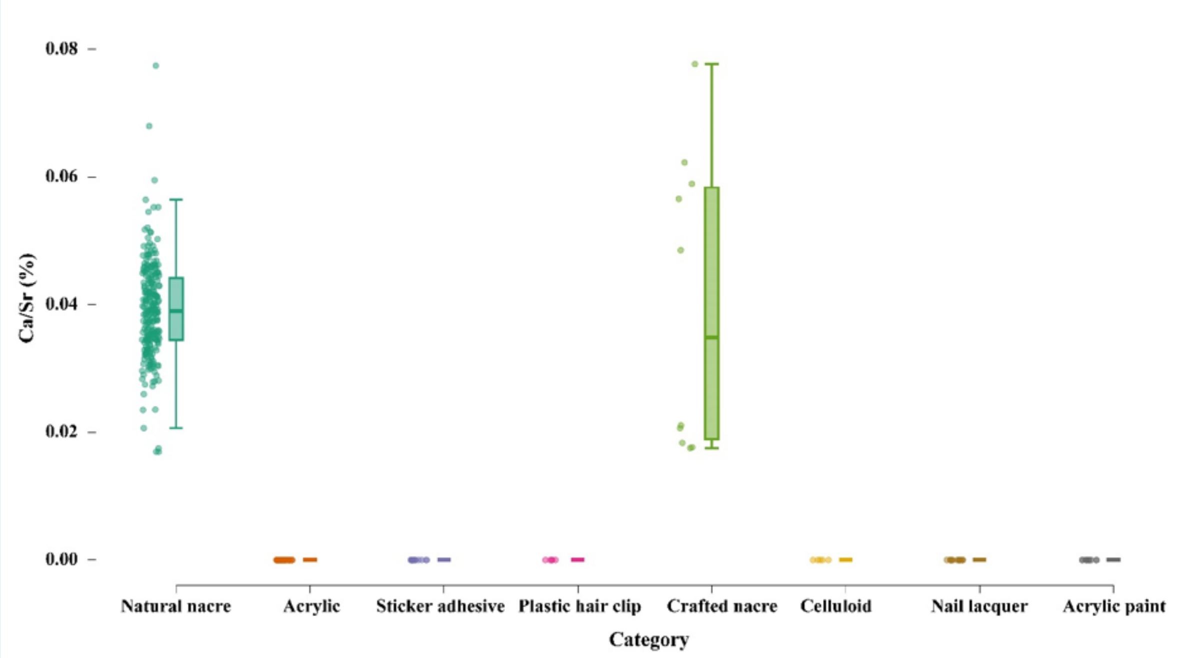

Figure 6: Ratio of the relative concentration (%) of calcium to the relative concentration (%) of strontium of various specimens measured by pXRF.

The pXRF software can estimate the cumulative percentage of light elements (LE), atomic number <16, present in a sample. The relative concentration of LE is estimated from the intensity associated with Bremsstrahlung background intensity [37]. This phenomenon occurs due to the low energy emitted from LE being reabsorbed into the sample matrix or detector itself and scattered into the background (Bremsstrahlung) radiation [37,38]. The graphical ploy of the LE percentage associated with the samples tested is shown in Figure 7 and it is important to note that synthetic polymers, which are primarily composed of low-Z elements (e.g., C, H, N, O) exhibited the highest LE percentages (Figure 7).

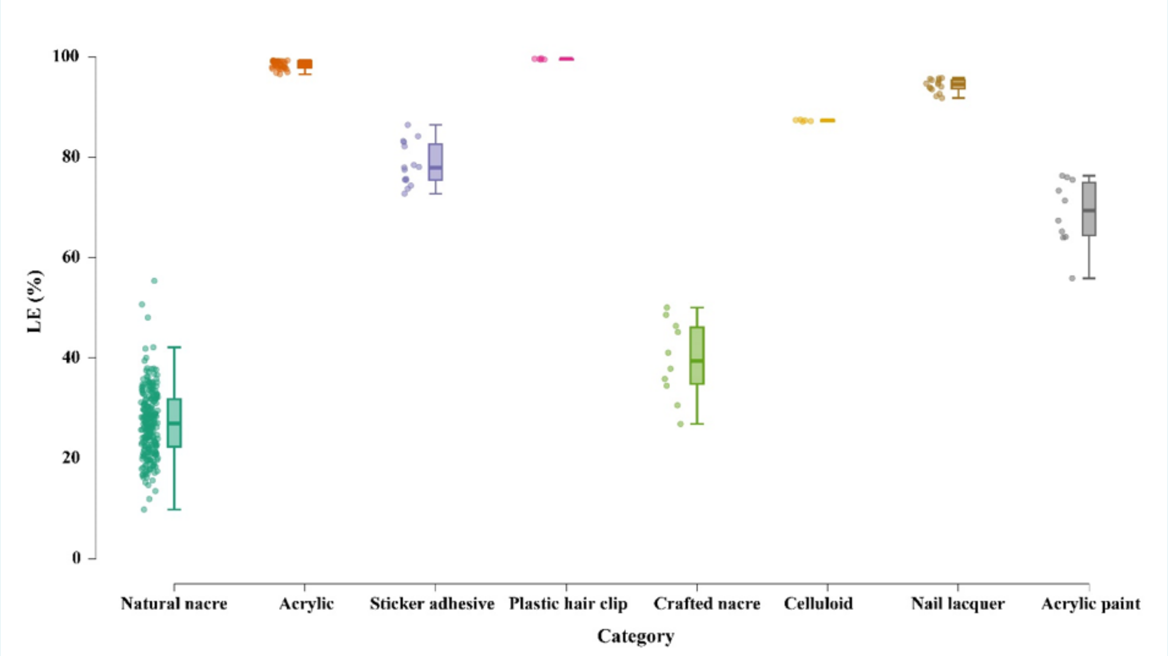

Figure 7: Relative light elements (LE) percentage estimation of various specimens measured by pXRF.

Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) Analysis

DRIFTS analysis was done by collecting spectra from reference nacre shell specimens (n = 5) (three specimens of *Haliotis rufescens*; one specimen of *Haliotis kamtschatkana*; and one specimen of *Pteria sterna*), commercial synthetic specimens (n = 18), and crafted nacre (n = 2). The DRIFTS spectra of the tested samples are shown in Figure 8 and includes the averaged spectrum (n = 5) collected from five nacre specimens as well as the spectrum from one synthetic acrylic (PMMA) sample and of one crafted nacre composite sample consisting of a combination of both nacre and synthetic polymer.

The spectrum associated with the natural nacre (Figure 8A) shows a broad peak at 1420 cm^{-1}, a unique peak 1085 cm^{-1}, a band stretch at 870-848 cm^{-1}, and doublet peaks between 699 and 716 cm^{-1} that may be characteristic of calcium carbonate, specifically in the form of aragonite [39,42]. Other distinguishing bands include a peak at 2926 cm^{-1}, a lower intensity peak at 2853 cm^{-1}, and a group of peaks at 1790 cm^{-1} and 1645 cm^{-1} that may be attributed to bond stretches and vibrations of the organic matrix [39,42]. In contrast, the acrylic (PMMA) spectrum is distinct from the spectrum of the natural nacre where the peaks associated with aragonite are absent (Figure 8B). The acrylic (PMMA) spectrum also showcased a set of peaks that may suggest an organic moiety between ~3066 cm^{-1} and 2800 cm^{-1}; a C=O bond stretch or vibration peak at 1745 cm^{-1}, and possible unique peaks suggesting C-C-O bond presence at ~1246 cm^{-1} and ~1200 – 1155 cm^{-1}.

DRIFTS analysis of the crafted nacre showed the spectrum to be like that of a variety of polymers and inconsistent with the reference spectra of nacre-producing mollusks. As previously stated, the manufacturer of the crafted nacre claimed that this material was a mixture of synthetic polymer and natural nacre flakes, and the DRIFTS analysis confirms that the spectrum was consistent with reference spectra of epoxy resin (Table 4). When comparing the spectrum of the crafted nacre (Figure 8C) to the natural nacre and acrylic (PMMA) spectra (Figure 8A and 8B), characteristic peaks and band stretches of esters that were seen in the acrylic spectrum are also observed in the crafted nacre spectrum. A small set of peaks that likely are associated with organic moieties are seen at 3018 cm^{-1} – 2800 cm^{-1} in the crafted nacre spectrum similar to the acrylic (PMMA) sample. Additionally, an ester element is also seen in the crafted nacre sample with peaks at 1745 cm^{-1}, 1254 cm^{-1}, and ~1116 cm^{-1}.

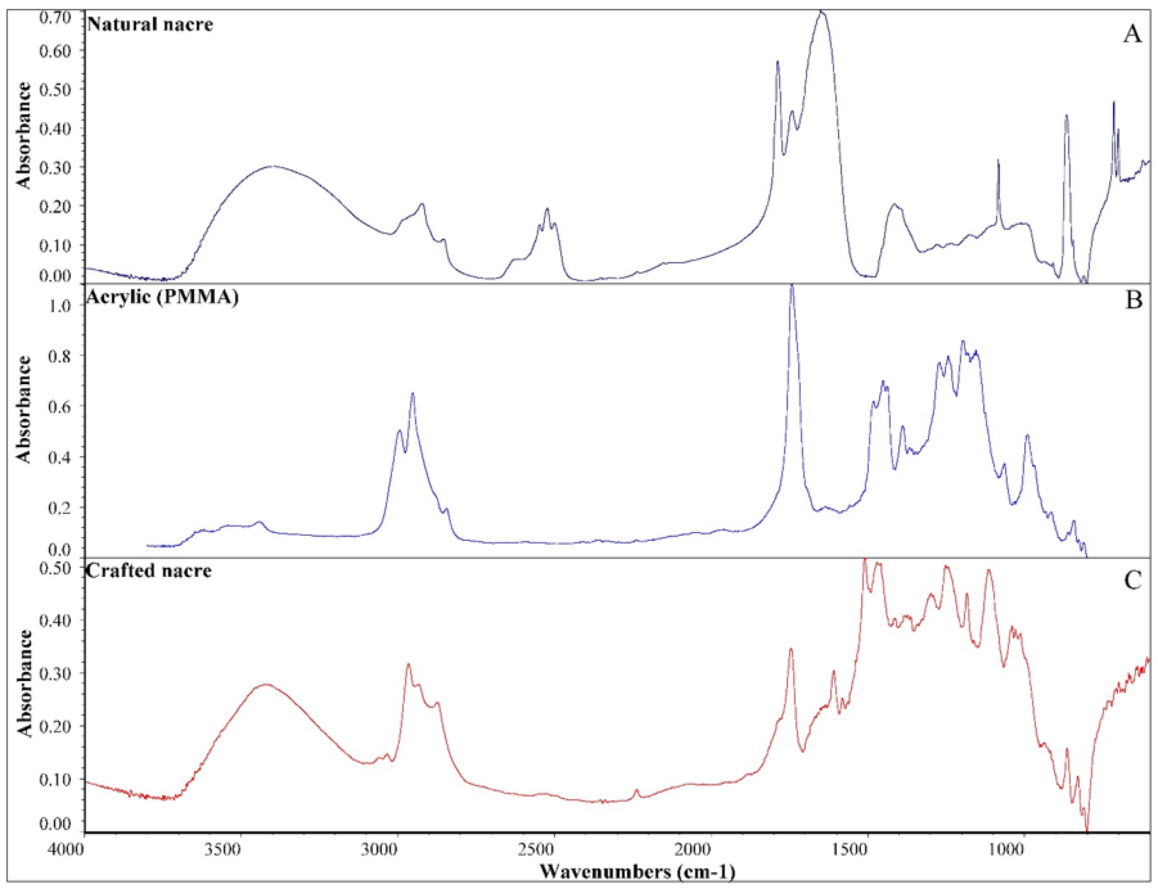

Figure 8: Natural nacre averaged DRIFT spectra of nacre shell (n = 5) specimens including one *Haliotis kamtschatkana* (pinto abalone), three specimens of *Haliotis rufescens* (red abalone), and one *Pteria sterna* (Pacific winged oyster) (A). The DRIFT spectrum of acrylic (PMMA) (B) and crafted nacre (C) are inconsistent with the natural nacre averaged spectrum.

Specimen	Library Search Match
Acrylic	Poly(methyl methacrylate) or PMMA
Acrylic paint	Vinyl ester, poly(vinyl propionate:acrylate)
Celluloid	N-Vinylpyrrolidone (60%)/vinyl acetate copolymer
Nail lacquer	Nitrocellulose, poly(vinyl propionate:acrylate)
Crafted nacre	Epoxy resin ester, epoxy resin
Sticker adhesive	Polyester terephthalate, tributyl citrate
Plastic Hair Clip	Alkyd resin

Table 4: Summary of DRIFTS library search results for synthetic specimens.

Discussion

The SciAps pXRF proved to be a useful tool to characterize the elemental composition of samples in this study. Results were acquired within minutes, requiring minimal data processing and could be used to determine relative percentage of elements in the sample matrix. Using pXRF we analyzed reference mollusk samples and have characterized the relative concentration of Ca, Sr and LEs, which are shown in Table 3 and in Figures 4 through Figure 7. The evaluation of nacre look-alike products indicated that only the crafted nacre products, which were claimed to be produced with natural nacre components, could not be excluded based on elemental analysis. All other samples had statistically different relative percentages of Ca, Sr and the LEs which allowed for their separation. The ratio of Ca/Sr displayed in Figure 6 enhanced the distinctiveness of the specimens that contained mollusk components. The crafted nacre, when visually inspected, appeared to contain a synthetic plastic component mixed with natural Mother of Pearl components and the elemental analysis profile found these samples to be indistinguishable from natural nacre shells.

Graphical representation of the pXRF LE percentage estimate (e.g., C, H, O, N) is visualized in Figure 7 and is a useful parameter to infer the possible presence of organic components. Curiously, the mollusk samples and the crafted nacre exhibited similar concentrations of the LEs. The organic source in the mollusk samples is surrounding all surfaces of the calcium carbonate crystals of the nacre, while in the crafted nacre the organic source is a manufactured polymer.

Analysis employing DRIFTS was useful to determine the molecular structure of organic compounds. Natural nacre is a combination of organic and inorganic elements and molecules, and the DRIFTS analysis could characterize the functional groups associated with it. An averaged spectrum of natural nacre from five mollusks – consisting of three species – is shown in Figure 8A. Sun J, et al. [6] and Macías-Sánchez E, et. al. [7] reported that nacre is composed of calcium carbonate crystals (95 wt%) and other organic molecules including proteins. Dauphin Y, et. al. [39], Santana P, et al. [42], and Tan TL, et. al. [3], reported that the calcium carbonate present in nacre has the crystal structure of aragonite and the band stretches seen in DRIFTS spectra in this study were consistent with the published literature. Shown in Figure 8A, the characteristic peaks that are associated with aragonite are observed at 1420 cm^{-1}, a second peak at 1085 cm^{-1}, a band stretch at 870-848 cm^{-1}, and doublet peaks between 699 and 716 cm^{-1}.

The spectra of two look-alike manufactured products which imitate Mother of Pearl are also shown in Figure 8. The acrylic (PMMA) sample (Figure 8B) is stated to be made of a synthetic polymer, while the crafted nacre sample (Figure 8C), was declared to be a blend of synthetic materials with natural nacre scales. For both of these look-alike materials, the strong peaks between ~3066 cm^{-1} and 2800 cm^{-1} likely accounts for the C-H bond behavior typical of polymers [43]. Other peaks observed in these manufactured materials are likely associated with esters (1745 cm^{-1}, ~1254 cm^{-1} – 1240 cm^{-1}, and ~1155 cm^{-1} – 1030 cm^{-1}) [43,44]. In conclusion, a simple visual examination of the spectra shown in Figure 8 is useful to distinguish between natural nacre and manufactured synthetic look-alike materials.

To summarize, to determine if a material was naturally produced from a mollusk, it must exhibit iridescence and contain nacre. Therefore, the criteria used in this study to determine if a material is naturally occurring nacre are as follows:

- Is the material iridescent?

This addresses the intrinsic physical properties of nacre which disperses incident light into colors of the visible spectrum. Non-iridescent material is excluded from further analyses.

- Does the material contain calcium and strontium? What is the LE percentage?

This addresses the anatomical features of nacre which is aragonite-based (e.g., calcium carbonate)

1. pXRF analysis reveals the relative concentration of calcium and strontium.
2. DRIFTS analysis infers the presence of aragonite and excludes synthetically manufactured look-alikes.
3. Comparison of these analytes against known reference samples of natural nacre is essential for a robust conclusion.

In our experience manufactured synthetic materials produced to imitate Mother of Pearl do not meet all of these criteria.

Conclusion

This study demonstrates that a trifurcated approach – combining visual, elemental, and organic analyses – is the most effective method for distinguishing natural nacre from synthetic imitations. This approach employs 1) visually confirming the presence of the unique iridescent sheen of nacre, 2) elemental analysis by pXRF, and 3) utilizing DRIFTS to characterize the organic components present.

Given the prevalence of synthetic, nacre-like finishes, we have shown that DRIFTS analysis alone can reveal the presence of a synthetic polymer. However, when more complex samples, such as crafted nacre, require analysis, it was beneficial to employ both pXRF and DRIFTS analysis. This combined approach revealed a composite material containing both natural nacre and a synthetic polymer, a finding that aligned with the manufacturer's claims.

Legal

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Acknowledgements

The authors thank Wildlife Inspector Catherine Yasuda (U.S. Fish and Wildlife Service) for donating the nacre shell specimens, Forensic Chemist Erin McClure-Price (U.S. Forest Service) for peer review, and Interlibrary Loans Coordinator John Fisher (U.S. Fish and Wildlife Service, National Conservation Training Center) for providing technical documents.

References

4. Madhav D, Buffel B, Moldenaers P, Desplentere F, Vandeginste V (2023) A review of nacre-inspired materials: Chemistry, strengthening-deformation mechanism, synthesis, and applications. Prog Mater Sci 139: 100777.
5. Chand S, Naidu S, Southgate PC, Simos T (2015) The relationship between tourism, the pearl and mother of pearl shell jewellery industries in Fiji. In: Pratt S, Harrison D (Eds.) Tourism in Pacific Islands: Current Issues and Future Challenges. Routledge, USA, pp. 148-164.
6. Tan TL, Wong D, Lee P (2004) Iridescence of a shell of mollusk Haliotis Glabra. Opt Express 12(20): 4847-4854.
7. Liu Y, Shingley JE, Hurwit KN (1999) Iridescence color of a shell of the mollusk Pinctada Margaritifera caused by diffraction. Opt Express 4(5): 177-182.
8. Boston University Physics Department (2000) Dispersion, diffraction and diffraction gratings. PY106 – Elementary Physics II.
9. Sun J, Bhushan B (2012) Hierarchical structure and mechanical properties of nacre: a review. RSC Adv 2(20): 7617-7632.
10. Macías-Sánchez E, Huang X, Willinger MG, Rodríguez-Navarro A, Checa A (2025) Organic macromolecules transport a significant proportion of the calcium precursor for nacre formation. Acta Biomater 191: 140-148.
11. Bio-glitter (2020) Glitter colour effects – what they are and how they work.
12. Zanini MLDO, Fonseca LM, Piecha CR, Corrêa CDPL, Dode LB, Zavareze EDR, Diaz PS (2024) A review of conventional and environmentally sustainable glitter. Environ Qual Manag 34(2): e22322.
13. Yurtsever M (2019) Tiny, shiny, and colorful microplastics: Are regular glitters a significant source of microplastics? Mar Pollut Bull 146: 678-682.
14. Blackledge RD, Gaenzle K, Jones EL Jr (2010) Holographic glitter. The McCrone Group; Materials Analysis, Modern Microscopy.
15. Amazon (2025) AOHOCA 2pcs nature bobbe abalone shell pattern with acrylic scale slabs handles, DIY knife sword making supplies material.
16. Amazon (2025) Thickness 1.5 mm 100% solid nature paua abalone knife handle flat shell blank scales inlay material slab-1.
17. ExchangeRates.org.uk (2025) Fiji dollar to US dollar history: 2013.
18. Etsy (2025) Natural white mother of pearl shell rectangle slab – 13x18mm, 15x20mm, 18x25mm, 20x30mm, 25x35mm.
19. Amazon (2025) GOMMO blue paua shell veneer sheet enhanced for inlay and overlay flat.
20. Simard NS, Militz TA, Kinch J, Southgate PC (2021) From past to present: Construction of a dataset documenting mother-of-pearl exports from a Pacific Island nation, Papua New Guinea. Front Mar Sci 8: 762610.
21. U.S. Fish and Wildlife Service (2013) Commercially importing and exporting jewelry made with wildlife. U.S. Fish and Wildlife Service, USA.
22. Seattle Aquarium (2025) Species recovery: Pinto abalone.
23. Friel B (2020) Delicious and now endangered: Can the pinto abalone make a comeback? Encyclopedia of Puget Sound.
24. EDAX (2018) Orbis Micro-XRF system. Smart Insight.
25. Sun X, He M, Wu J (2022) Crystallographic characteristics of inorganic mineral in mammoth ivory and ivory. Minerals 12(2): 117.
26. Tiley-Nel SL (2018) Bones and ivory. In: The Encyclopedia of Archaeological Sciences. Wiley, USA, pp. 1-4.
27. Delvie's Plastics (2025) Pearl cast acrylic sheet.
28. MakerStock (n.d.) Acrylic (pearlescent white); Pearlescent cast acrylic (PMMA) sheet.
29. Etsy (2025) Pearl shimmer acrylic colors 1/8" thick sheet blanks, ready for laser cutting.
30. Speedball Art (2023) Speedball acrylic paint, titanium white datasheet version 01.
31. Amazon (2025) Celluloid dark blue pearl guitar or bass pick – 1.2 mm extra heavy gauge – 351 shape – 1 pack.

32. OPI (2025) Nail lacquer – lucky lucky lavender; ingredients.

33. Amazon (2025) REVLON ultra HD snap nail color, natural rich glossy polish, 016 Get Real; ingredients.

34. Ulta Beauty (2025) Mega pigment nail lacquer, shimmers – Crushin' on blue; ingredients.

35. Amazon (2025) 2pcs abalone shell sticker (300 mm × 200 mm) abalone sheets veneer imitation abalone hand stickers for craft handmade decoration with backside tape (C).

36. Amazon (2025) 2pcs abalone shell sticker (300 mm × 200 mm) abalone sheets veneer imitation abalone hand stickers for craft handmade decoration with backside tape (E).

37. Amazon (2025) Generic abalone sea shell effect blue green hair claw clamp clip.

38. Espinoza EO, Scanlan MD, McClure PJ, Baker BW (2012) Forensic analysis of black coral (Order Antipatharia). Forensic Sci Int 216(1–3): 73-77.

39. Gillikin DP, Lorrain A, Navez J, Taylor JW, André L, et al. (2005) Strong biological controls on Sr/Ca ratios in aragonitic marine bivalve shells. Geochem Geophys Geosyst 6(5): Q05009.

40. Hunt AM, Speakman RJ (2015) Portable XRF analysis of archaeological sediments and ceramics. J Archaeol Sci 53: 626-638.

41. Declercq Y, Delbecque N, Grave JD, Smedt PD, Finke P, et al. (2019) A comprehensive study of three different portable XRF scanners to assess the soil geochemistry of an extensive sample dataset. Remote Sens 11(21): 2490.

42. Dauphin Y, Lo C, Németh G, Sandt C, Cuif JP (2025) Structure versus composition: A comparative study across scales. Faraday Discuss 253: 1-17.

43. White WB (1974) The carbonate minerals. In: Farmer VC (Ed.) The Infrared Spectra of Minerals. Adlard & Son Ltd., UK, pp: 239-246; 273.

44. Chakrabarty D, Mahapatra S (1999) Aragonite crystals with unconventional morphologies. J Mater Chem 9(11): 2953-2957.

45. Santana P, Aranda DA (2021) Nacre morphology and chemical composition in Atlantic winged oyster Pteria colymbus (Röding, 1798). PeerJ 9: e11527.

46. Thermo Fisher Scientific Staff (2011) Fundamentals of analysis for FTIR training manual. Thermo Fisher Scientific, USA.

47. Smith B (2018) The C=O bond, part VI: Esters and the rule of three. Spectroscopy Solutions for Materials Analysis.