

Article

Practical Dyeing and Technical Imaging: Replicating a Colonial Feather Insignia from Mexico

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Abstract: A colonial feather insignia from New Spain dating to the late 16th century is one of a group of seven unique feather objects kept in museums in Austria, Germany, and Mexico. The insignia represents a highly skilled example of a featherworking tradition documented in historical sources such as the Florentine Codex. In order to make a replica for the National Museum of Anthropology in Mexico City (MNA), an interdisciplinary team carried out technical and material studies before preparing the necessary raw material. At the centre of this work are bird feathers dyed with organic dye and naturally coloured feathers that cover most of the insignia's surface. By working with historical documents, artisans, reference collections of bird skin, and the application of multiband imaging (MBI) and fibre optic reflectance spectroscopy (FORS), it was possible to identify both the bird species and the organic dye used or naturally presented in the feathers. Dyeing experiments to colour-match the different shades of red were conducted by applying traditional recipes and materials. The true value of this research is not necessarily in the finished product or outcome but in the journey itself—specifically in the methods developed and the practical experience gained along the way.

Keywords: Mesoamerican featherwork; replica; cochineal; bird feathers; feather dyeing; multiband imaging (MBI); fibre optics reflectance spectroscopy (FORS)



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1. Introduction

The object of this interdisciplinary research is a 16th century colonial feather insignia (Figure 1) from Mexico (Weltmuseum Wien, inv. no. 43.381), which represents a highly skilled example of a featherworking tradition called *amantecayotl* in classical Nahuatl, the language that was spoken in various regions of Mesoamerica around the 15th and the 16th centuries.

The insignia belongs to a unique group of seven pre-colonial and early colonial feather objects preserved in Europe and Mexico: a feather headdress, known as *penacho* (Weltmuseum Wien, inv. no. 10.402, Austria), four feather shields (Weltmuseum Wien, inv. no. 43.381, Vienna; Württemberg State Museum, inv. no. KK_orange_6 and E1402, Germany; Chapultepec Castle, inv. no. 10-92265, Mexico), and a disc or chalice (National Museum of Anthropology, inv. no. 11.3213, Mexico). These objects are testimonies to a colonial history and witnesses of the encounter between the Old and New Worlds.

Thousands of similar objects were destroyed by the *conquistadors*, and hundreds were shipped to Europe where they were distributed amongst the nobility and royalty [1].



Figure 1. Feather insignia (side **a,b**), New Spain (E.16.c.), inv. no. 43.381. @ KHM-Museumsverband.

Due to their fragility and susceptibility to insect infestation, only a few have survived in museums. To compensate for the absence of such featherwork in historical collections and for conservation reasons, the National Museum of Anthropology in Mexico City (MNA) has in the past commissioned replicas of the above-mentioned *penacho*, one shield, and the disk from contemporary *amantecas*. Such featherworks are important to museum visitors because of their iconic status and their role in the exhibition narrative and are therefore on permanent display. By using replicas, it is possible to expand the lifespan of the original objects (e.g., preventing light damage) while ensuring public accessibility.

The replicas at the MNA differ from the original in terms of design, size, and material for three major reasons: contemporary craft practices are different from the ancient techniques; feathers from culturally important bird species of the Aztec period are endangered today; and all replicas were made from reference images, without sight of the originals, with the exception of the disc.

Unlike most feather replicas at the MNA, a replica of the feather insignia will be made to be as close as possible to the original. In the future, it will serve as an important didactic tool in the Mexica Hall of the MNA. Therefore, the insignia was examined in detail and individual steps in the craft were reproduced as mock-ups in the conservation laboratory in Vienna. A visual artist will make the replica based on conservation research and his own visual examination during a residency at the Weltmuseum Wien. Since the replica is understood to be an object made with reference to scientific findings, the process will also enable current knowledge on this ancient craft to be reviewed and expanded upon.

When feathers are only present in small fragments, it is very difficult to identify the bird species non-destructively. The feathers identified on the insignia offered the opportunity to test whether it is possible to draw conclusions about biopigments and structural

colours using multiband imaging (MBI) in combination with fibre optic reflectance spectroscopy (FORS). In the field of ornithology and animal behaviour, spectroscopic studies to qualify and quantify feather colour are widely accepted [2–4]. In cultural heritage, FORS and MBI are already well-established methods to study dyes and pigments in textiles and paintings [5–8] but are rarely applied to featherwork, except for by Daher [9] or Pearlstein [10]. However, ultraviolet-induced visible luminescence imaging (UVL) has become an important tool for the light sensitivity assessment of keratin [11], for feather cleaning studies [12], and for feather identification [13].

2. Historical Background

2.1. The Art of Featherworking—*Amantecayotl*

Various historical sources were used in this research. The most important source for the craft of the *amantecas* is the so-called Florentine Codex [14], or *Historia General de las cosas de Nueva España*, written between 1575 and 1577 in the city of Tlatelolco by Bernardino de Sahagún and a group of local informants, indigenous collaborators, and local painters. It is a twelve-volume encyclopaedia covering the life, nature, religion, philosophy, history, and culture of the ancient Nahuatl-speaking people of Central Mexico. Book IX (chapter 18–21) is dedicated to the *amantecayotl*. *Amantecayotl* is a specialised craft in which naturally coloured and dyed feathers are glued to a paper support or tied together.

The individual processes of feather selection and preparation by *amantecas* are vividly documented. Three types of *amantecas* operated in two kinds of settings. The *calla amanteca* produced military paraphernalia and sold their products in the markets [15]. The *tecpan amanteca* were associated with the imperial palace; they made luxury gifts and elaborate costumes worn in ceremonies, festivals, and combat [16,17]. A third group, the *calpixcan amanteca*, produced the most precious objects for the Mexica sovereign [18]. All three types of *amantecas* were closely linked to the nobility, as the use of feather paraphernalia and other luxuries was limited to the ruling class [19]. We do not know whether these *amantecayotl* categories were maintained during colonial times.

The Mesoamerican tradition in feather art was promoted by the Spanish missionaries after the *Conquista* and mostly consisted of Christian devotional images and liturgical luxury items for the European royalties, nobles, and leaders of Catholicism. The feather mosaics made by New Spain *amantecas* with depictions of Christ, the Virgin Mary, and saints had already reached Europe, Asia, and Africa as well as the north and south of the American continent at the end of the 16th century [20].

2.2. The Art of Dyeing Feathers Red

The “Memoria sobre la naturaleza, cultivo y beneficio de la grana” by José Antonio de Alzate y Ramírez from 1777 [21] is considered one of the most remarkable studies and the first essay on American cochineal (*Dactylopius coccus*), the breeding and harvesting of this insect, and the use of this dye in New Spain. Cochineal was a tribute paid by many indigenous people, first to the Aztecs and later to the Viceroyalty of New Spain. None of the red dyes from the Old World—kermes (*Kermes vermilio*), Polish cochineal (*Porphyrophora polonica*), and lac (*Kerria lacca*)—could compete with the deep red colour derived from the dye extracted from cochineal (*Dactylopius coccus*) [22]. The dye was in great demand among the Spanish elite for dyeing fabric, and until 1785, the end of the mercantile system, large quantities of the cochineal production was destined for export to Spain [23].

In the Florentine Codex, indigenous informants use various names for the red colour, such as “chili-red” [24] (51v), “scarlet red” [24] (58r), or “red like fresh blood” [24] (217r). Feathers were not only dyed red with cochineal (*Dactylopius coccus*) [24] (216r–217r) but also yellow with, for example, Barba de león (*Cuscuta tintoria* Mart. Former

Engelm., a variety of the parasitic plant dodder) [24] (217v) or the petals of the sunflower *Cosmos sulphureus* [24] (217r).

In the past, dyers used, and still use, a variety of plants and minerals for the dyeing process in Mexico. The wool is pre-treated for degreasing in a solution of *tequesquite* water [25], *tequesquite* being a natural mineral salt containing compounds of sodium chloride, sodium carbonate, and sodium sulphate.

Natural dyes can generally be used for direct dyeing, but permanent results are only obtained with tanning agents or mordant dyes. Mordanting with metal salts binds the dye to the fibre, improves the colour fastness, and makes the colour more radiant. In addition, depending on the mordant, different shades can be achieved with the same dye [26]. One of the most common mordants was an aluminium-based salt; the feather dyers added alunogen, $\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$, an aluminium sulphate mineral, and then saltpetre (nitrate of sodium or potassium) to the dyebath [24] (65r) in a meta-mordanting process. Alunogen occurs naturally as a rare mineral found in volcanic environments and was used for refining colour and for washing [24] (219v). *Tezhuatl* leaves [27] from a shrub (*Miconia* sp.), which are used as a herbal mordant, are another aluminium-containing source [28]. The leaves are boiled together with alum and *tlaliyac* (copperas, i.e., iron(II) sulphate) to dye not only wool, silk, or feathers but also *tochomitl* (rabbit hair) red [24] (218v). The feather dyers of the past had most likely experienced that an orange-red colour is achieved by adding acidic material to the cochineal dye bath, e.g., the leaves of wood sorrel (*Oxalis* spp.), which contain soluble salts of oxalic acid [27,29,30], and that the use of alkalis (such as soda ash) results in a blue-red to bright purple colour.

3. Identification of Naturally Coloured and Dyed Bird Feathers for Making a Replica of a Colonial Feather Insignia from Mexico

This paper presents experimental research to characterize bird feathers and their colourants on the insignia based on historical sources, visual examination, and spectral imaging. In order to create an authentic replica, it is crucial to work with feathers from the same bird species. This ensures that the specific characteristics of the feathers, such as colour and texture, can be accurately reproduced. The second part of the project is experimental research on the dyed feathers present. This includes methods for identifying red-dyed feathers and the development of recipes for dyeing contour feathers in two shades of red. Colour measurements were not performed; the red feather colour was assessed visually by direct comparison with the original object. It was much more about concentrating on the practical part and learning as much as possible about traditional dyeing processes and materials for colour matching.

3.1. Feather Insignia: Naturally Coloured Bird Feathers

The naturally coloured feathers of the insignia were identified by visually comparing them with bird skin collections at the Natural History Museum in Vienna and the Pabellón Nacional de la Biodiversidad at UNAM in Mexico City as part of this research project. Additionally, the identification of the feathers was guided by historical sources such as the Codex Mendoza [31]. Most of the naturally coloured feathers are derived from parrots from the family Psittacidae. The long blue wing feathers are from the scarlet macaw (*Ara macao*); they are blue on the dorsal and yellow-orange on the ventral side. The decoratively glued dark-green, yellow-green, and yellow feather tips are from an *Amazona* (parrot) species. The iridescent green feather tips may originate from the domestic wild turkey (*Meleagris gallopavo*) or Muscovy duck (*Cairina moschata*).

The yellow feathers with orange speckles for the petal design were deliberately placed as accents by *amantecas* (Figure 2). Initially, it was assumed that these were colour accents

that were subsequently applied with a dye. However, microscopic examination confirmed that this is a natural colour variation common to the plumage of *Amazona* species (lesser wing covert, head).



Figure 2. Flower motif: yellow feathers and orange speckles, red and pink feathers.

Each part of a naturally coloured feather (shaft, barbs, barbules) can display different colours, and the colour mechanisms in the keratin structure play a role of varying importance in colour rendition. Feather colours originate from biopigments (carotenoid, psittacofulvin, melanin, porphyrin, turacin, turacoverdin), structural, and iridescent structural colours. In contrast to the biopigment colours, the structural colours are created by light scattering at the interfaces of biomaterials—keratin and melanin—and air, each of which has a different refractive index [32]. Most blue, violet, and green colours are a combination of structural colours and biopigments that are created in the barbs. The iridescent colour is produced in the barbules by coherent scattering of light by layers of keratin and melanin granules [33]. Melanin is an effective absorbent of UV and IR radiation [34].

Most of the insignia feathers are from parrots, which derive their colour from the yellow, orange, and red biopigment psittacofulvin. The colour of green parrot feathers is a combination of yellow psittacofulvin in the cortex, melanin granules in the medulla, and the keratin structure (Figure 3) [35]. Psittacofulvin is restricted to the order Psittaciformes (parrots, cockatoos, lorries, and lorikeets) [36] and is a useful marker for identifying these birds. It can exhibit a natural bio-luminescence when exposed to a UV source, and this feature can aid in the identification of bird feathers [36]. However, and this has been noted elsewhere [12,37], it is not possible yet to make a clear distinction between luminescent and non-luminescent psittacofulvin chromophores of similar composition.

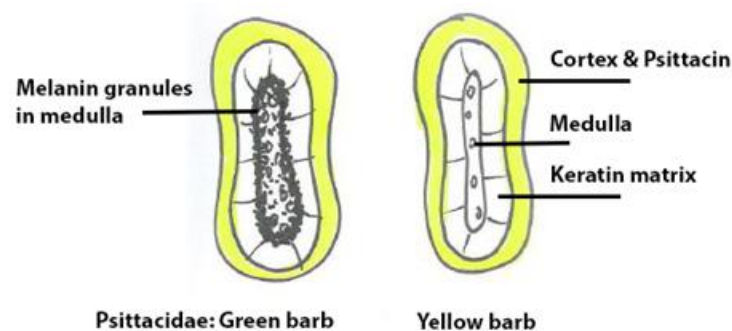


Figure 3. Cross section of a green and yellow Psittacidae barb. Drawing by Renée Riedler, based on Tinberg et al. [38].

The list of birds used by the *amantecas* for their featherwork, which are symbolically coded [39], covers around 20 species [40–42]. These birds were raised in captivity and their

feathers were collected, sold, or given as a tribute. The Codex Mendoza [30] is the primary source on how feathers and feathered objects reached the city of Tenochtitlan, the capital to the Aztec empire, and circulated there. Some of the most colourful feathers belong to bird species living in ecosystems located far from Tenochtitlan; they would have arrived there as commercial goods or tribute from tropical areas south of the empire and along the coast of the Gulf of Mexico. We do not have information about how feathers arrived in the workshops of the convents in New Spain.

3.2. Examination of Dyed Bird Feathers

An important first step was to identify the feathers, both in terms of bird species and colourants, that form the insignia. While most of the vibrant colours are created by biopigments in combination with organized keratin structures as outlined in the introduction, the pink and red feathers are dyed. The colour of the red feathers is a combination of red dye and most likely psittacofulvin biopigments, which are responsible for the yellow, orange, or red colours specific to parrots. Although these dyed feathers resemble naturally red feathers, there are three characteristics that indicate the presence of dye: The feathers have a red vane, a brown shaft, and a pink plumulaceous part, which is usually white, brown or grey in other birds. Another distinguishing feature is the even red colouration on both sides of the feather, while undyed feathers only show the colour on the ventral side. A final hint is the glossy red spots of undissolved dyestuff scattered all over the feather. Glossy red spots are also found on the pink-dyed feathers.

Based on historical sources, visual examination, and scientific studies on two comparable objects (feather shields at the WMW, inv. no. 43.381 and at Chapultepec Castle, inv. no. 10-92265) [43], the authors of this paper considered that there is a high probability that the feathers are dyed with American cochineal (*Dactylopius coccus*). The colour of the red dyed feathers is still vibrant; the authors of this paper anticipate only minor changes in hue and saturation. Insect-derived dyes such as cochineal are fairly light-stable, with fading rates that remain below that of blue wool 3 [44,45], and feathers containing psittacofulvin biopigments were found to be of medium sensitivity [9]. However, the feathers dyed pink are in very poor condition. This is indicated by a severe loss of barbules, which is to be expected given their age and the fact that they have been exposed to chemical and thermal processes during dyeing. Light damage is also visible in the many white spots on the otherwise pink feathers. There are no reliable records of previous exposure to light but it is known that the insignia was part of the collection of Archduke Ferdinand II of Tyrol (1529–1595) at Ambras castle (Innsbruck), where most of his items were kept in cabinets. The insignia was brought to Vienna in the late 19th century and has been on display for long periods of time ever since.

4. Materials and Methods

4.1. Multiband Imaging (MBI)

In order to support our research with accessible and non-destructive equipment, the research team used multiband imaging (MBI) in combination with fibre optic reflectance spectroscopy (FORS). The requirements for the MBI equipment were that it should remain within a limited budget and that it should be mobile (Table 1).

All images were acquired with a Nikon (Vienna, Austria) D850 camera body modified for “full spectrum” (sensitivity between about 360 and 1100 nm). A Nikon Nikkor 50 mm f/1.8D AF lens was used for all the photos. The camera was operated in fully manual mode and tethered to a computer, using the software ControlMyNikon 5.6 to allow sharp focusing. The camera for MBI takes five images, with the filters (UV-VIS-IR) and light sources being changed manually. The CHSOS Robertina technical photography filters set

“<https://chsopensource.org/technical-photography-filters-set/>” (accessed on 14 February 2024), reference targets, and radiation sources summarised in Table 2 were used. Post-processing procedures of the VIS, IRR, UVL, and UVR images and the creation of IRRFC and UVRFC images were carried out using Adobe Photoshop CS6. The workflow is based on the Charisma protocol [46] and a flowchart provided by Cosentino [8].

Table 1. Equipment for multiband imaging (MBI) at the Weltmuseum Wien.

Camera	Modified Nikon D850 Camera, internal filter disassembled (360–1000 nm) - Visible-reflectance (VIS), ultraviolet-reflectance (UVR), infrared-reflec tance (IRR) - UV-induced Vis luminescence (UVL) 2 false colour images (IRRFC, UVRFC)
Filter	CHSOS Robertina TF filters set (UV/VIS/IR)
Radiation source	- UV LED 365nm SableLED® lamps - Tungsten, Quenox 5000 K, 60 W - Halogen, Osram 6444Os, 12 V, 50 W
Target	- RMI Conservation target - CHSOS MBI-MSI calibration card - Teflon target (PTFE)
Software	- ControlMyNikon - Adobe Photoshop Lightroom - Adobe Photoshop CS6

Table 2. FORS (fibre optic reflectance spectroscopy) setting.

Spectrometer	Detector	Spot Size	Angle	Lamp	Software
Gorgias by CHSOS (Viagrande, Italy), 350–900 nm	Toshiba TCD1304DG	Ø 1 mm	45°	10 W halogen lamp	F. Menges “Spectragryph—optical spectroscopy software”, Version 1.2.16, 2022, http://www.effemm2.de/spectragryph/

4.2. Fiber Optic Reflectance Spectroscopy (FORS)

Fiber optic reflectance spectroscopy (FORS) uses fibre optics for directing the white light onto a small spot (typical diameter about 1 mm) to be analysed. The light reflected by the surface can be collected by the same fibre bundle using different angles (typically between 45 ° and 90 °) of detection and varying spectroscopic ranges from the UV to the near IR regions.

The Gorgias reflectance spectrometer for art by Cultural Heritage Science Open Source “CHSOS, <https://chsopensource.org/reflectance-spectroscopy-system/>; Table 2” (accessed on 14 February 2025) used in this study is made of a 10 W halogen lamp and a Toshiba TCD1304DG linear array detector offering a range of detection in the visible region from about 350 to 900 nm. It is equipped with an optic fibre of 7 × 600-micron core fibres (6 excitation fibres, 1 collection fibre) surrounded by a stainless steel tubing for extra strength. The fibre is 1 m long and it has a 45 ° adapter for reflectance measures.

FORS measurements were taken of the differently coloured feathers of the colonial insignia as well as examples of all the dyed and undyed reference feathers using the 45° setting and measurement times between 0.5 and 1 s per spectrum; single spectra were recorded. Spectra evaluation was performed using the OpenSource software Spectragryph (<https://>

www.ffmpeg2.de/spectragryph/about.html), which is capable of generating first derivatives of the FORS spectra for determining inflection points besides the absorption maxima.

4.3. Scanning Electron Microscopy with Energy Dispersive X-ray Detection (SEM-EDX)

Scanning electron microscopy with energy dispersive X-ray detection (SEM-EDX) was used to verify the composition of selected materials used during the dyeing experiments, i.e., alum and *tequesquite* from the Sonora market (see supplementary spectra).

The SEM examinations were carried out in cooperation with the University of Applied Arts Vienna, Institute of Conservation, on the carbon-coated samples using a JEOL JSM-IT200 scanning electron microscope equipped with a tungsten cathode and a JEOL SDD EDX detector. Applying the high-vacuum mode and an excitation voltage of 20 keV, a maximum resolution of up to 3 nm can be achieved.

4.4. Feather Dyeing: Materials and Recipes

For the preliminary dyeing studies in a laboratory setting in Vienna, commercially available material was purchased as outlined in dye books and manuscripts [26,29] (Table 3). The feathers were mordanted with alum and dyed with cochineal or dyed without any mordant. Subsequently, variables such as different mordants, e.g., tin(II) chloride, and pH values were explored, and further experience was gained in feather dyeing workshops in Mexico. Experimental dyeing studies conducted in Vienna incorporated dye recipes and additives which had been explored and collected in Mexico.

Table 3. Supply for feathers, dye, and mordant.

Feather	Material	Source
Chicken	White, semi-plumaceous	www.atelier-renato.at ; feathers imported from China
Chicken	White, semi-plumaceous	www.moonlightfeather.com
Goose	White, pennaceous “shoulder feathers”; translucent vane	www.atelier-renato.at ; feathers from a local farm in Austria
Scarlet macaw	Red, pennaceous	Natural History Museum Vienna; birdskin
Turkey	White, plumaceous	www.moonlightfeather.com
Dye		
Cochineal	Cochineal (silver grey) from Canary Islands, contains 18–22% carminic acid	Kremer Pigmente #3040
	Cochineal (red) from Peru	La Nopalera farm (Tlapanochestli), San Bartolo Coyotepec, Oaxaca
	Cochineal (red)	Schoenfaerberey®
Mordant		
Alum	Potassium aluminium sulphate, $KAl(SO_4)_2 \cdot 12H_2O$	Kremer Pigmente #64100.12100.136
	Naturally occurring mineral, aluminium sulphate resp. alunogen, $Al_2(SO_4)_3 \cdot 17H_2O$	Sonora market, Mexico City
	<i>Tezhuatl</i> leaves (plant based Al salt)	Oaxaca
Tin(II) chloride	$SnCl_2$	Neuber’s Enkel
Copper(II) sulphate	$CuSO_4$	Museum stock, unknown supplier
Iron(II) sulphate	$FeSO_4$	Museum stock, unknown supplier

Feathers: For our experimental dyeing protocols, we used five types of feathers (Table 3). All feathers were in good condition, which was confirmed by conducting a simple water repellence test: a water droplet was not absorbed by the feather but rolled off after the feather was slightly twisted. It is therefore assumed that they had been only minimally pre-treated (e.g., gentle cleaning).

Dyestuff: For this study, we used American cochineal (*Dactylopius coccus*) purchased in Oaxaca (Mexico) and from two different European suppliers (Table 3). The cochineal insects were prepared in different ways before dyeing: grinding, soaking overnight, or removing the waxy coating by soaking the insects in an alcohol solution (ethanol:H₂O = 1:3) for one minute; these modifications did not visibly change the dyeing result.

Recipes: With regard to the amount of material, liquor ratio, and dyeing time, we tried to adhere to proven recipes [26,29] to ensure a certain comparability of the results. Demineralised water was used as the solvent throughout, and the maximum temperature was limited to 70–80 °C to protect the integrity of the feathers [47].

Mordant: A dye series with various water-soluble metal salts (based on aluminium, iron, and copper) has been produced. Alum (potassium aluminium sulphate), aluminium sulphate (alunogen), and plant leaves containing aluminium [48] were included in the study. Alunogen was purchased from the Sonora market, which was established in the 1950s. It is one of the most emblematic and popular markets in Mexico City, where you can find traditional raw materials that are not available in other markets.

Although tin(II) chloride was not yet known at the time, it was included in the dye series, along with other mordants, to determine a range of colours that could be achieved on the feathers. It produces bright orange-red colours when combined with cochineal. In addition, experiments were carried out with *tezhuatl* leaves, a plant-based mordant. The leaves were collected by the weavers Victoria Villaseñor Oviedo and Carlos Barrera Reyes in San Mateo del Mar, Oaxaca. Mrs. Oviedo recalled that her mother used them for dyeing with cochineal. The leaves were boiled in water for an hour and the resulting liquid was taken to Mexico City to experiment with it as a mordant.

pH value: For the dyeing process itself, six dye liquors with pH values from 3 to 8 [49] were prepared. The pH was measured with a pH/mV Hand-Held Meter (Wissenschaftlich-Technische Werkstätten GmbH). The colour of carminic acid in solution appears light orange at low pH, changes to red in the weakly acidic and neutral range, and turns violet in the alkaline range. The dye liquors were used in combination with alum and tin(II) chloride, as these mordants produce the desired red hues. The pH was adjusted with acetic acid (CH₃COOH) and sodium hydroxide (NaOH) solutions.

Additives: Citric acid and lemon juice were added to the alum mordant (pH 2.5) and the dye bath. Dyers in Mexico add lemon juice at the end of the cochineal dye bath to obtain a range of colours from red to orange. This practice is widespread in Los Altos de Chiapas, as with the Gómez Pérez family from Chacoma Tenejapa and the Pérez Hernández family from San Andrés Larráinzar. Lemon was not available until after 1493, when it was introduced to America by Christopher Columbus. Another acid used to supplement the alum mordant was tannic acid, which did not affect the pH but did influence the colour hue.

Tequesquite, a salty crust that forms when marshes dry up, from a medicinal shop at Sonora market was purified before use. The undissolved granular material was filtered off and the clear solution evaporated until a white powder remained, containing the soluble fraction of the natural mineral salts, i.e., compounds of sodium chloride, sodium carbonate, and sodium sulphate. Feathers soaked in alkaline solutions such as *tequesquite* are severely damaged and the resulting colour is not red but a light pink. Traditionally, *tequesquite* was used as a mordant [50], because in its naturally occurring, unfiltered form, it also contains

small amounts of Al and Fe, which are only present in trace amounts after the purification (dissolution and filtering) process (see supplementary SEM-EDX spectra).

5. Results and Discussion

5.1. Multiband Imaging (MBI)

Used in MBI mode, the camera captured four images (Figure 4) of each feather colour (Table 4), and during the following image processing, additional UVR and IRR false colour images (UVRFC and IRRFC) were generated, respectively.



Figure 4. Multiband images (MBI) and false colour images: Set-up by Weltmuseum Wien (see details in Figure 5).

UV-induced visible luminescence imaging (UVL): The pink feathers emit pink luminescence in the UVL image (a). This is typical for a red dye such as cochineal on a keratin substrate. Feather keratin alone shows a white to blue UVL [11,12]. The red feathers seen in the visible image absorb UV and appear very dark in the UVL image. This can be explained by a higher concentration of the dye (b) in combination with the presence of biopigments (c); both also obscure the UVL of the keratin. The yellow (d) and yellow-green feathers (e) show UV bioluminescence, which is typical for some yellow parrot feathers [12,36]. However, when the melanin concentration is high, as in the dark green feathers (f), this usually quenches the UVL. The keratin of the light-blue feathers (h) emit a light blue colour in the UVL image.

Infrared-reflected imaging (IRR) and infrared-reflected false colour (IRRFC): The feather keratin is largely transparent to IR radiation, as suggested by the light appearance of the IRR image. The feathers containing melanin appear significantly darker, and the other colourants also have an influence on the observed reflection behaviour. This difference in transparency/reflectance behaviour is evident from the IRRFC image. In the IRRFC image, some red dyes like cochineal appear orange (a, b, c). The yellow and yellow-green parrot feathers with psittacofulvin biopigment (d, e) appear white and light blue, respectively, in IRRFC. The colour difference between both images is most likely due to the presence of melanin in the yellow-green feathers. In general, it is noticeable that structural and iridescent structural feathers appear in various purple colours in the IRRFC image (e, f, g, h).

UV-reflected imaging (UVR) and UV-reflected false colour (UVRFC): The feathers absorb UV radiation to varying degrees. The red-dyed (c) and the green iridescent feathers (g) absorb the most and the light blue feathers (h) the least UV radiation. The differences in reflectance behaviour, resulting from different pigments and structures, are also evident from the UVRFC image. In the UVRFC image, some red dyes like cochineal appear olive green (a, b, c). The yellow (d), yellow-green (e), and dark green (f) parrot feathers with psittacofulvin biopigment appear in various shades of purple in the UVRFC image. The colour difference is most likely due to the different melanin content in the feathers. Structural blue appears bright blue and green iridescent feathers appear a dark blue in the UVRFC image (g, h).

Table 4. Summary of the main observations made from the MBI images of the feather insignia (Figures 4 and 5).

#	Location of Colour	Bird Spec.	UVL	IRRFC	UVRFC	Pigment
a, b	Pink barbs, pink barbules	unknown spec.	Pink shades	Light orange	Olive	Dye
c	Red barbs, red barbules	unknown spec.	Dark red	Orange	Dark olive	Dye, biopigment
d	Yellow barbs, yellow barbules	<i>Amazona</i> spec.	Bright yellow	White	Purple	Psittacofulvin
e	Yellow-green barbs, translucent barbules	<i>Amazona</i> spec.	Bright yellow-green	Light blue	Purple	Psittacofulvin, melanin, structural colour
f	Dark-green barbs, brown barbules	<i>Amazona</i> spec.	-	Light purple	Dark purple	Psittacofulvin, melanin, structural colour
g	Brown barbs, iridescent-green barbules	Turkey or duck	-	Dark purple	Dark violet	Melanin, iridescent-structural colour
h	Light-blue barbs, translucent barbules	Scarlet macaw (<i>Ara Macao</i>)	Light blue	Light purple	Light blue	Melanin, structural colour

Although it is not possible to confirm the presence of cochineal in the pink and red feathers without applying additional methods such as FORS or high-performance liquid chromatography (HPLC), the false colours detected in the IRRFC and UVRFC images, together with the low levels of luminescence observed in the UVL image, give strong hints to the presence of either an insect-based red dye or a plant-based dye present at high

concentrations [7]. As plant dyes commonly used in Europe, such as madder, or similar local Mexican species (for example, *Relbunium* spp.) are not known to have been used for feather dyeing in Mexico in that period, the most likely candidate for an insect-based dye would be cochineal, as its use and availability at the period is well-known [21–24].

For a better understanding of the red feathers, MBI images of a macaw feather, a cochineal dyed macaw feather and dyed chicken feathers were obtained (Figures 6–8), and the main observations are summarized in Table 5.



Figure 5. (a–h) Details of multiband images (MBI) of chevrons with feathers from different bird species.

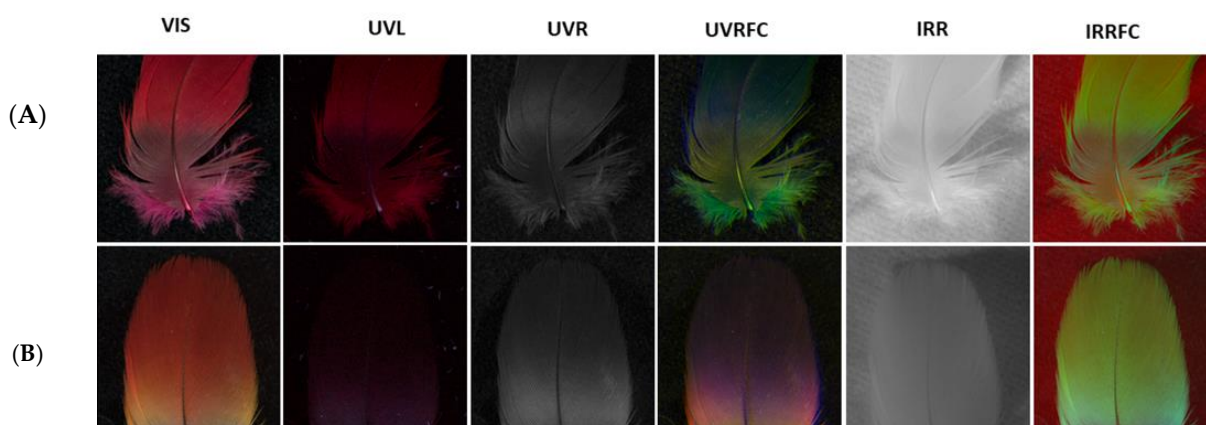


Figure 6. Multiband images (MBI) (VIS, UVL, UVR, UVRFC, IRR, and IRRFC) on black background of a cochineal-dyed scarlet macaw feather and alum mordant (A) and naturally coloured scarlet macaw feather (B).

UV-induced visible luminescence imaging (UVL): The dyed macaw feather emits red (Figure 6A) and the dyed chicken feathers show red to purple (Figures 7 and 8) luminescence in the UVL image. The red colour observed is the fluorescence of the keratin through the filter of the dye. The undyed macaw feather appears dark in the UVL image.

Infrared-reflected imaging (IRR) and infrared-reflected false colour (IRRFC): The feather keratin is largely transparent to IR radiation, as suggested by the light appearance of the IRR image (Figures 6A, 7 and 8). The colourants also have an influence on the observed reflection behaviour. This difference in transparency/reflectance behaviour is

evident from the IRRFC image. The macaw feathers appear yellow in colour (Figure 6A,B) and the dyed chicken feathers an orange colour (Figures 7 and 8) in the IRRFC image. The white chicken feather remains white in the IRRFC image (Figure 7a).

Table 5. Summary of the main observations made from the multiband images (MBI) in Figures 6–8.

	Bird Spec.	UVL	IRRFC	UVRFC	Pigment
Figure 6A	Scarlet macaw	Pink and red	Yellow and orange	Olive, green, and blue	Alum, cochineal, psittacofulvin
Figure 6B	Scarlet macaw	-	Yellow	Pink and purple	Psittacofulvin
Figure 7a	Chicken	White	White	Yellow	White structural colour
Figure 7b	Chicken	Pink	Light orange	Yellow and olive	No mordant, cochineal
Figure 7c–h	Chicken	Red to purple	Orange	Green	Alum, cochineal, pH 3–pH 8
Figure 8a'–f'	Chicken	Red	Orange	Green	Tin(II) chloride, pH 3–pH 8
Figure 8g'	Chicken	Red	Orange	Green	Alum, cochineal, tannic acid
Figure 8h'	Chicken	Red	Orange	Olive	Alum, cochineal, citric acid

UV-reflected imaging (UVR) and UV-reflected false colour (UVRFC): In contrast to white feathers, dyed, and biopigmented feathers absorb most of the UV radiation. The differences in reflection behaviour resulting from the different pigments and structures are also clearly visible in the UVRFC image. In the UVRFC image, the dyed macaw feather (Figure 6A) has a green downy part, an olive-coloured vane, and a blue tip. The colour of the undyed macaw feather in the UVRFC image ranges from pink at the base to purple closer to the tip. The white feather appears yellow (Figure 7a), and the colour of the unmordanted dyed feather is a mixture of yellow and olive. The dyed chicken feathers appear in olive and green hues (Figures 7 and 8).

For comparison purposes and to investigate whether it is possible to distinguish between carotenoid and psittacofulvin biopigments, MBI was performed on a random selection of available feathers (Figure 9, Table 6) with known biopigments [51]. We identified two problems: firstly, the background colour affects the colour of the spectral images generated for translucent feathers. To solve this problem, two feathers were placed on top of each other. Secondly, the age of the feathers and their state of preservation are different, which affects the intensity of the bioluminescence.

UV-induced visible luminescence imaging (UVL): The white and yellow feather of the sulphur-crested cockatoo (*Cacatua galerita*) (Figure 9A') and the yellow feather of the blue and yellow macaw (*Ara araurana*) (Figure 9E') emit a bright orange luminescence in the UVL image, which is typical for many parrots [52]. Both feathers were documented shortly after they were collected from the bird, which might have an impact on the intensity of the bioluminescence. The yellow tail feather of the montezuma oropendula (*Psarocolius montezuma*) (Figure 9D') with carotenoid pigmentation appears in a light yellow colour in the UVL image, similar to the VIS image. Stains from soiling are visible at the base of this feather. The roseate spoonbill (*Platalea ajaja*) (Figure 9B') and the scarlet ibis feather (*Eudocimus ruber*) (Figure 9C') appear in similar colours in the UVL image, less so in the VIS image. Although unavoidable stray light somewhat distorts the colour appearance in this image and was taken into account, it did not influence the interpretation. The green parrot (Figure 9F'), the

scarlet macaw (*Ara Macao*) (Figure 9G'), and the brown (Figure 9H') feathers do not emit luminescence in the UVL image due to their melanin content.

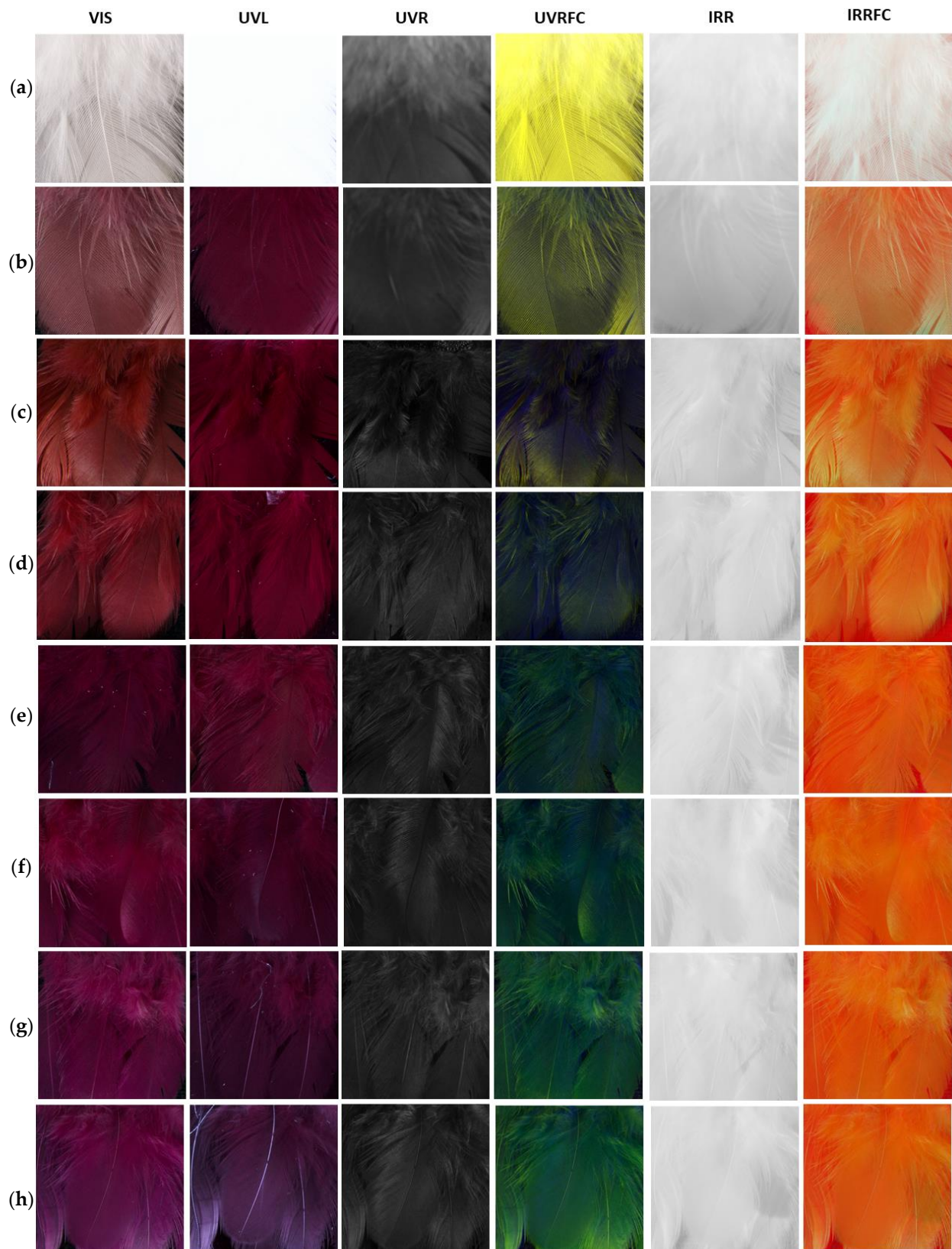


Figure 7. Multiband images (MBI) of white feathers (a), cochineal-dyed feathers without mordant (b), and cochineal-dyed feathers with alum mordant, pH 3–pH 8 (c–h).

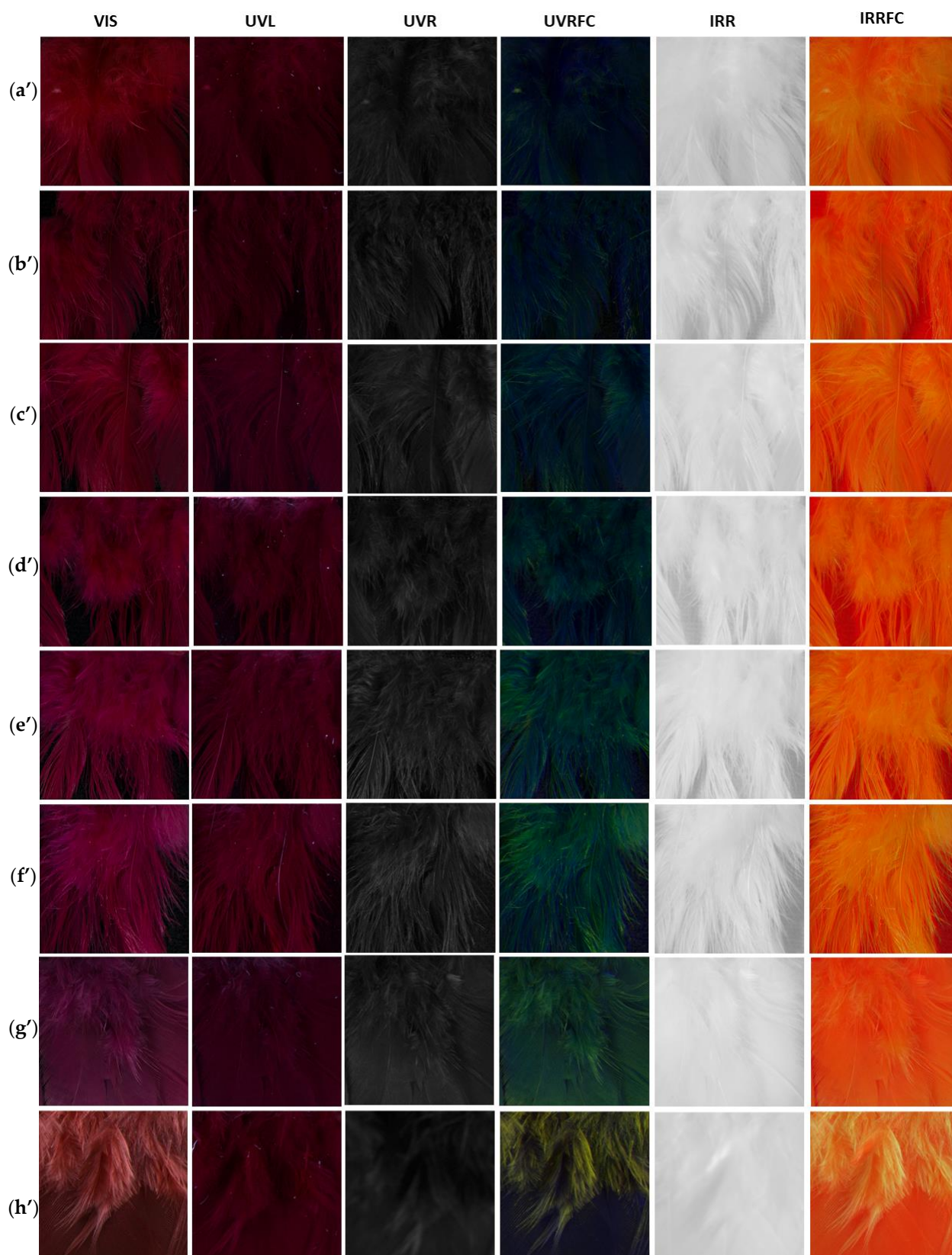


Figure 8. Multiband images (MBI) of cochineal-dyed feathers and tin(II) chloride mordant, pH 3–pH 8 (a'–f'); cochineal-dyed feathers and alum mordant, tannic acid (g'); cochineal-dyed feathers and alum mordant, citric acid (h').

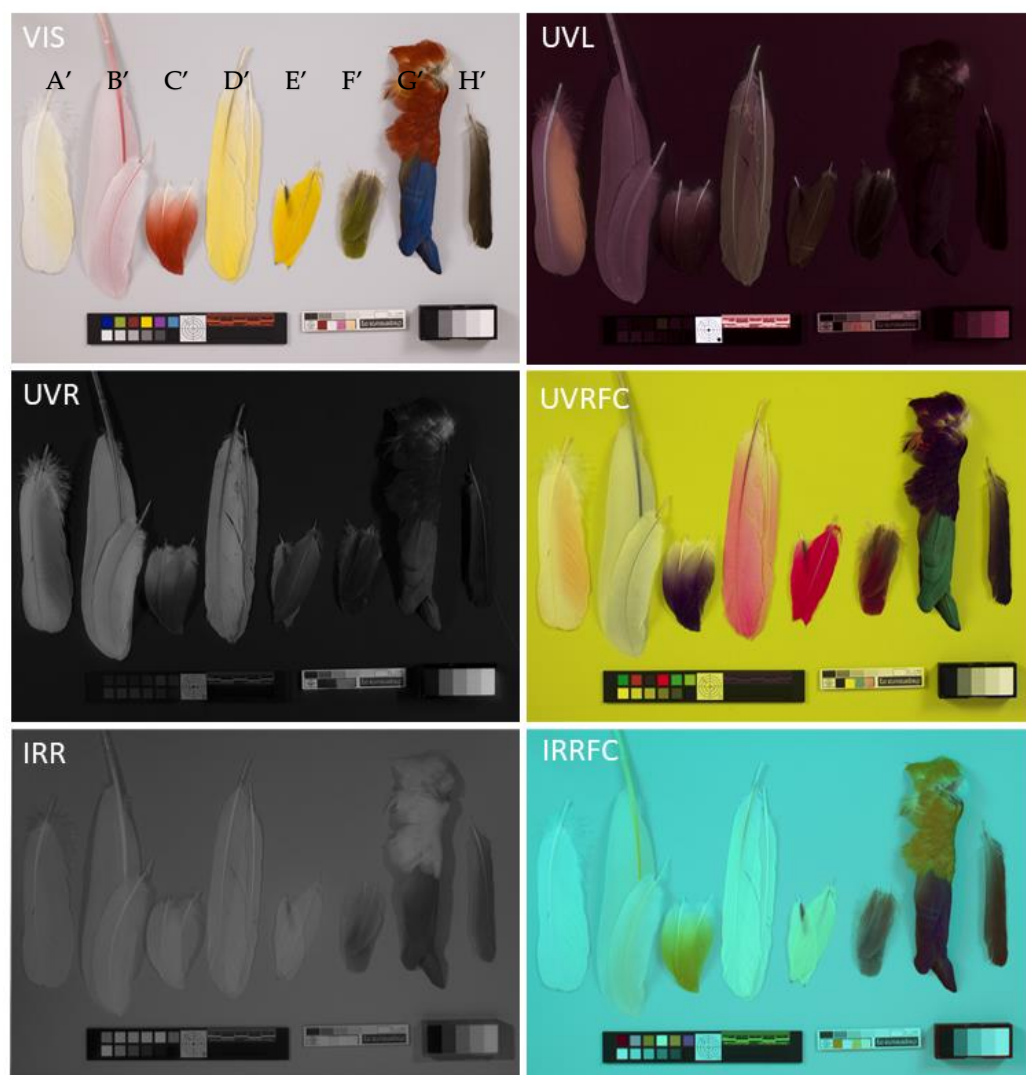


Figure 9. Multiband images (VIS, UVL, UVR, UVRFC, IRR, and IRRFC) of a feather selection representing a range of biopigments on a neutral grey background. From left to right: Sulphur-crested cockatoo (A'), roseate spoonbill (B'), scarlet ibis (C'), montezuma oropendula (D'), blue and yellow macaw (E'), unspec. parrot (F'), scarlet macaw (G'), and brown feather (H').

Table 6. Summary of the main observations made from the Multiband images (MBI) in Figure 9.

#	Bird Species	Pigment	VIS	UVL	UVRFC	IRRFC
A'	Sulphur-crested cockatoo (<i>Cacatua galerita</i>), coll. 2023	Psittacofulvin	Light yellow	Dark yellow	Pale orange	White
B'	Roseate spoonbill (<i>Platalea ajaja</i>), coll. 2007	Carotenoid	Light pink	Light pink	Light blue	Light yellow
C'	Scarlet ibis (<i>Eudocimus ruber</i>), coll. 2007	Carotenoid	Orange	Dark orange	Dark violet	Dark yellow
D'	Montezuma oropendula (<i>Psarocolius montezuma</i>), coll. 2007	Carotenoid	Yellow	Light yellow	Light purple	Light yellow
E'	Blue and yellow macaw (<i>Ara araurana</i>), coll. 2023	Psittacofulvin	Dark yellow	Orange	Dark purple	Light yellow
F'	Parrot, n.d., taxidermy	Psittacofulvin, melanin	Green	-	Dark purple	undef.
G'	Scarlet macaw (<i>Ara Macao</i>)	Psittacofulvin	Red	-	Dark violet and pink	Orange
	Scarlet macaw (<i>Ara Macao</i>)	Melanin	Dark blue	-	Turquoise	Dark violet
H'	Brown wing feather, n.d.	Melanin	Brown	-	Brown	Brown

Infrared-reflected imaging (IRR) and infrared-reflected false colour (IRRFC): The feather keratin is largely transparent to IR radiation, as suggested by the light appearance of the IRR image. The melanin-containing keratin appears significantly darker, and the other pigments have little to no influence on the observed reflection behaviour. Some difference in transparency/reflectance behaviour is evident from the IRRFC image: the feathers based on psittacofulvin or carotenoid biopigments appear white (Figure 9A') or yellow in different levels of brightness (Figure 9B'–E') or orange (Figure 9G'). The colour of the green feather (Figure 9F') in the IRRFC image is an indefinable mixture of greys. The blue part of the scarlet macaw wing (Figure 9G') shows brown, but also some blue hues, and the brown feather (Figure 9H') appears light brown in the IRRFC image. The brown colours in the IRRFC images are indicative of their melanin content.

UV-reflected imaging (UVR) and UV-reflected false colour (UVRFC): The feathers absorb UV radiation to varying degrees. The white part of the cockatoo (Figure 9A'), the pink spoonbill (B'), and the yellow oropendula feather (D') reflect the most UV radiation and the green parrot (F'), the red macaw (G') and the brown feather (H') the least. The differences in reflectance behaviour, resulting from different pigments and structures, are also evident from the UVRFC image.

The yellow part of the cockatoo feather appears in a pale orange in the UVRFC image (A'). This colour differs significantly from the colour of the yellow macaw (E') and green parrot feather (F'), which appear in a dark purple colour.

It should be noted that the cockatoo belongs to a different bird family (Cacatuidae) to the macaw and unknown parrot (green feather). The spoonbill appears in a subtle blue (B') and the scarlet ibis in a dark purple (C'). The third feather based on carotenoid pigmentation, the yellow oropendula feather, displays a pink-magenta colour in the UVRFC image (D'). The red macaw feathers appear in a dark purple (G'), the blue macaw in turquoise (G'), and the brown (H') in a very similar brown colour in the UVRFC image.

5.2. Fiber Optics Reflectance Spectroscopy (FORS)

A usual way of plotting the absorption information inherent in FORS reflectance spectra is using the $\log(1/R)$ coordinates, known as apparent absorption. Here, the absorption bands clearly discriminate the carotenoid-based yellow colour of the montezuma oropendula reference feather (Figure 10, spectrum c) from the yellow colour of the chevron (Figure 10, spectrum a) and flower petal feathers within the colonial insignia (Figure 10, spectrum b). The carotenoid-based yellow feather of the oropendula has absorption peaks at approximately 404, 430, 457, and 487 nm, whereas the spectra of the insignia's yellow feathers show broad absorption bands around 450 and 475 nm [9]. The main difference is the lack of structure in the spectra from the yellow areas of the insignia compared to the reference spectrum (carotenoid). As the yellow feathers have been identified as being from a parrot species, it is likely that the pigment is a psittacofulvin, based also on comparison to work including reference spectra by Tinbergen et al. [38].

In the same way, an insect-based dye such as cochineal can be identified by its absorbance maxima around 525 and 560 nm (Figure 11a) and an inflection point at approximately 590 nm (Figure 11b) [5,53]. Using the first derivative plot for our FORS spectra, the inflection point for the feathers of the original insignia could be detected at 607/608 nm (Figure 11b, spectra a and b), which is in good accordance with the alum-mordanted cochineal-dyed chicken feather, applying pH 4 (Figure 11b, spectrum d). Changing the pH value (e.g., to pH 3) during the dyeing experiments leads to a clear shift in the inflection point of the corresponding FORS spectrum for the dyed chicken feathers (Figure 11b, spectrum c) to a higher wavelength. By using tin(II) chloride as a mordant instead of alum at pH 4 and 3, the inflection points are shifted to lower wavelengths, i.e., between 590 and 600 nm (FORS data shown in the Supplementary Material). It is well known that loss of

spectral structure is a function of dye concentration [7], and this is the case for the spectra shown in Figure 11a.

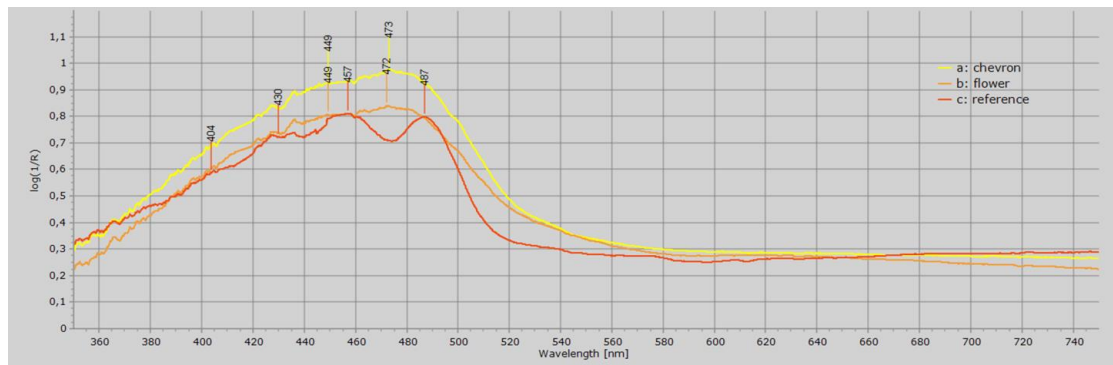
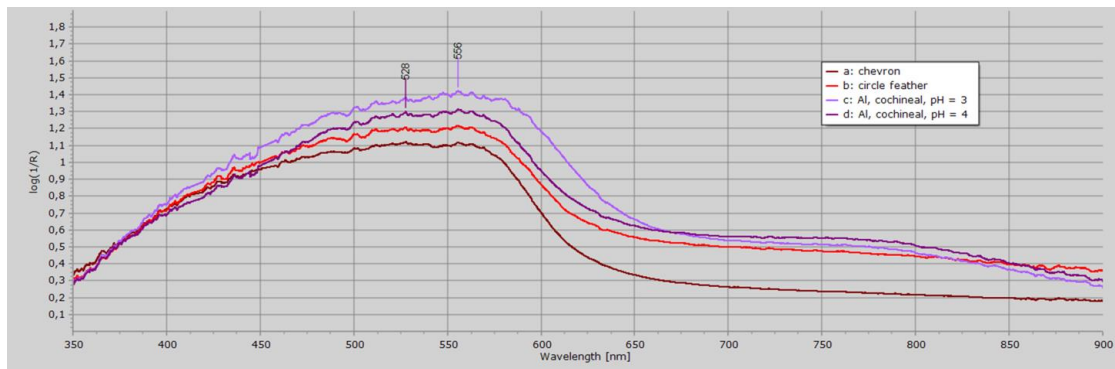
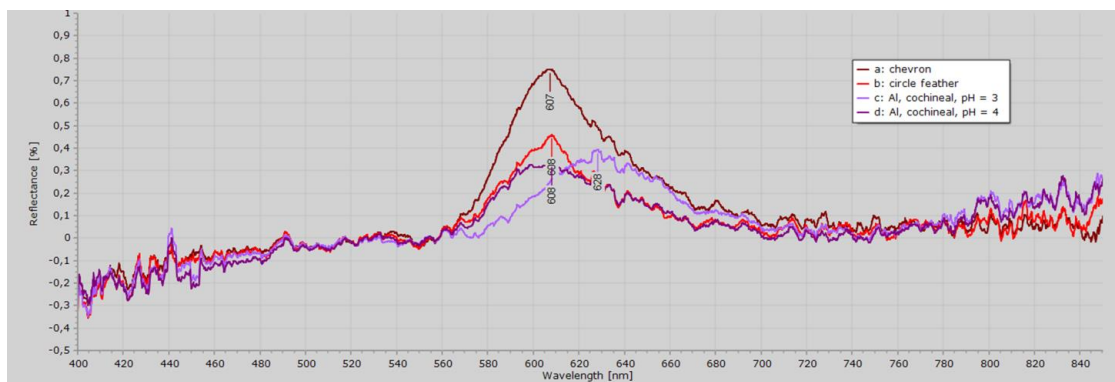


Figure 10. FORS spectra plotted in $\log(1/R)$ coordinates: the yellow feathers of the insignia (a: chevron; b: flower) show clearly different spectra compared to the carotenoid-based yellow feathers of the montezuma oropendula tail (c: reference).



(a)



(b)

Figure 11. (a) FORS spectra plotted in $\log(1/R)$ coordinates: Red-dyed feathers of the colonial insignia (a: chevron; b: circle feather) compared to alum-mordanted cochineal-dyed chicken feathers (c: Al, cochineal, pH 3; d: Al, cochineal, pH 4). (b) First derivative of FORS spectra as shown in (a). The inflection point of the spectra for the red-dyed feathers of the colonial insignia (a, b) closely matches the inflection point of the spectrum for the alum-mordanted/cochineal-dyed chicken feather applying pH 4 (d). Changing the pH from 4 to 3 in the dyeing experiments clearly shifts the inflection point in the corresponding spectrum (c).

5.3. Dyeing for Making a Replica: Observations

The colour of the red- and pink-dyed feathers for the disc and chevron design was approximated by focusing on the effects of different chemicals and pH levels. The aim was to create a recipe for the pink-coloured feathers and one for the red-coloured feathers based on a visual comparison with the original object.

Feathers: Two types of feathers from different sources were used: chicken feathers and goose shoulder feathers. Since the feathers come from different sources, they were cleaned in different ways, possibly with cleaning agents. We cannot rule out the possibility that some preen oil was still present. A colour difference (with and without mordant) (Table 7a–d) can be attributed to the different structure of the two types of feathers because one can rule out the possibility of substances remaining on the feather after exposure to the dye bath (with and without mordant bath).

Table 7. Recipes (a–r): Feather colour variation based on the type of feather, the basic dye recipe, the mordant and additives.

Recipe #	Feather	Recipe	Mordant	Additives	Image
a	Goose	Kirby, van Bommel, Verhecken 2014	without mordant		
b	Chicken	Kirby, van Bommel, Verhecken 2014	without mordant		
c	Goose	Kirby, van Bommel, Verhecken 2014	alum $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$		
d	Chicken	Kirby, van Bommel, Verhecken 2014	alum $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$		
e	Chicken	Kirby, van Bommel, Verhecken 2014	copper sulphate	pH 4	
f	Chicken	Kirby, van Bommel, Verhecken 2014	iron sulphate	pH 4	

Table 7. Cont.

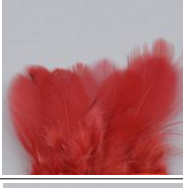
Recipe #	Feather	Recipe	Mordant	Additives	Image
g	Chicken	Kirby, van Bommel, Verhecken 2014	Alum $KAl(SO_4)_2 \cdot 12H_2O$	pH 4	
h	Chicken	Kirby, van Bommel, Verhecken 2014	Tin(II) chloride	pH 4	
i	Chicken	Kirby, van Bommel, Verhecken 2014	Alum $KAl(SO_4)_2 \cdot 12H_2O$	Cream of tartar	
j	Chicken	Arroyo Ortiz 2020	<i>Tequesquite</i>		
k	Turkey	Barrera Reyes 2023	Alum <i>tezhuatl</i>		
l	Chicken	Arroyo Ortiz 2020		Citric acid	
m	Chicken	Arroyo Ortiz 2020	Alum $KAl(SO_4)_2 \cdot 12H_2O$	Citric acid	
n	Chicken	Arroyo Ortiz 2020	Alum $KAl(SO_4)_2 \cdot 12H_2O$ <i>tequesquite</i>	Citric acid	
o	Chicken	Arroyo Ortiz 2020	Alum $KAl(SO_4)_2 \cdot 12H_2O$	Tannic acid	

Table 7. Cont.

Recipe #	Feather	Recipe	Mordant	Additives	Image
p	Chicken	Kirby, van Bommel, Verhecken 2014	Alunogen $\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$		
q	Blue and yellow macaw	Kirby, van Bommel, Verhecken 2014	Alum $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$		
r	Scarlet macaw	Arroyo Ortiz 2020	Alum $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$	Citric acid	

Cochineal: The use of different cochineal products and preparation methods had no visible influence on the colour. Soaking the feathers overnight, variations in the dyeing time of up to Table 7h, and re-soaking in the dye bath as well as a second dye bath did not affect the result.

Mordant: Dyeing feathers with cochineal and alum ($\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$) without additives produced a bluish-purple hue, which was significantly different from the desired red hues of the insignia feathers. Pre-mordanting with alunogen ($\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$) resulted in a more reddish hue (Table 7p) and tin(II) chloride produced bright orange colours (Table 7h). Copper and iron sulphate created shades of purple (Table 7e–f).

pH-value: The pH of the dye bath played a crucial role in determining the final colour. In acidic conditions, the carminic acid dye bath turned red, whereas in alkaline conditions, it turned blue-violet. In order to achieve a red colour, it was expedient to dye with pH 4 (Table 7g).

Supplementary additives: Supplementary additives such as tannic acid in combination with alum produced a dark red hue with a blue tinge (Table 7o), and citric acid shifted the colour towards an orange hue (Table 7l). However, the most accurate red, closest to the insignia feathers, was obtained by dyeing yellow (Table 7q) or orange (Table 7r) macaw feathers with cochineal and alum.

6. Conclusions

Multiband imaging of bird feathers: We demonstrated the use of multiband imaging (MBI) techniques to investigate biopigments and structural feather colours in birds. The study showed both the potential and the limitations of this method for non-invasive analysis of feather colours. When prior knowledge of the bird species is available, as it is for the insignia, specific patterns can be recognized in the MBI images that are related to the type of biopigments. The study struggled to differentiate between colours based on carotenoids and psittacofulvins. Additionally, it was challenging to find a pattern across feathers from different bird families that had psittacofulvin-based colouration. This suggests that birds from different families exhibit distinct MBI patterns although they share the same biopigment. A more comprehensive study that includes a systematic study of

feathers across genera, families, and species in combination with a study of the molecular composition of the biopigments would be required for more reliable conclusions.

What can be said with certainty is that several factors have influenced the outcome of MBI imaging: the state of preservation of the feathers, their structural features, the type and concentration of biopigments present in the feathers, and the type and concentration of dye.

Experimental research: Feather dyeing with cochineal: The formal design of the central motifs (butterfly and flower) is influenced by the European style of the time, but aspects of Mesoamerican origin prevail, among which the predominant use of red stands out. Depending on the context, pre-Hispanic cultures of Mexico assigned a symbolic meaning to the red colour. It can symbolize death and the underworld, or war, blood, and sacrifice; red can also refer to the ancestral time, the earth, and the force of light [54,55]. In this insignia, the presence of red, perhaps intentionally, permeates some of these indigenous concepts. Therefore, the replica project placed a particular focus on the dye study. As already demonstrated in many studies, cochineal is capable of producing a wide range of colours that are influenced by various factors, such as the chemical composition of the dye, the concentration, the type of fibres, the mordant used, and additives [56]. The main goal of this research was to develop a sound understanding of dyeing techniques and to work with materials that may have been used in the past and which are still known and used today.

For the pink colour, dyeing with cochineal without mordant proved to be the most effective, as it yielded pink goose and chicken feathers that matched the corresponding colours on the insignia (Table 7a,b). However, a dyeing recipe with mordant (Table 7j,k) will be chosen for the replica to ensure the colour remains permanent, even if the hue will vary. Another possibility would be to add potash to the dye bath with cochineal to achieve a pink colour for alum-dyed materials [26].

Dyeing chicken feathers with mordant and cochineal at pH 4 (Tables 7g and 8) came closest to the desired red colour but was less saturated and lacked luminosity. The perfect colour match, also in terms of luminosity and saturation, was achieved by dyeing a yellow and orange macaw feather (Table 9q,r). However, given that approximately 3600 feathers had to be dyed for the replica, this was not realistic as there were insufficient resources available.

Table 8. Recipe for the best colour-matching of red-dyed feathers (see Table 7g).

Mordant bath	1.8 g feathers 90 mL demineralized water 0.36 g potassium aluminium sulphate
	Dissolve the alum in water. Add the feathers and heat the mordant bath to max. 70–80° C, then maintain the temperature for one hour. Stir occasionally. Rinse thoroughly with water.
Dye bath	1.8 g mordanted feathers 110 mL demineralized water 0.22 g cochineal (carefully ground) pH 4 (adjusted with acetic acid CH ₃ COOH)
	Put the cochineal in a polyester mesh bag and soak it in water. Raise the temperature to 100° C and boil for one hour. Remove the bag, add the feathers, and adjust the temperature to max. 70–80° C. Maintain the temperature for one hour. Stir occasionally. Rinse thoroughly with water. Absorb water with blotting paper and blow-dry (with cold air).

Table 9. Dyed bird feathers which best match the pink, rose-coloured and orange-red feathers of the colonial insignia (a, b, q, r) and the undyed parrot feathers in comparison (s, t).

Recipe # (See Table 7)	Colonial Insignia	Dyed Sample	Insignia and Dyed Sample
a Pink (goose feather)			
b Rose (chicken feather)			
q Orange-red (yellow feather of blue and yellow macaw)			
r Orange-red (orange feather of scarlet macaw)			
Detail of insignia compared to undyed parrot feathers			
s scarlet macaw			
T blue and yellow macaw			

The recipe in Table 8 has only been used on a small scale so far; the next step is to carry out the dyeing process on a large scale to test the reproducibility. It is emphasized that working with natural dyes is associated with uncertainties, especially when repeating dyeing processes. Another important point is that the feathers used must be of comparable quality, size, and structure.

The research highlights that while it will not be possible to exactly replicate the dyeing process for feathers, the project has provided valuable insights into materials, techniques, processes and the significance of particular shades of red on pre-colonial and colonial feather objects.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/heritage8030085/s1>, Figure I. SEM-EDX spectrum of “alum”—most probably alunogen—from Sonora market, clearly showing the presence of aluminium sulphate instead of potassium aluminium sulphate. Figure II. SEM-EDX spectrum of uncleaned, i. e. unfiltered, tequesquite purchased from Sonora market. Figure III. SEM-EDX spectrum of cleaned tequesquite. The insoluble components based on Si, Ca, Mg, Al and Fe are mostly removed during the cleaning process. Figure IVa. FORS spectra plotted in $\log(1/R)$ coordinates: Red dyed feathers of the colonial insignia (a: chevron; b: circle feather) compared to tin(II) chloride mordanted/cochineal dyed chicken feathers (c: Sn, cochineal, pH 3; d: Sn, cochineal, pH 4). Figure IVb. First derivative of FORS spectra as shown in Figure IVa. The inflection point of the spectra for the red dyed feathers of the colonial insignia (a,b) diverge from the inflection point of the spectra for the tin(II) chloride mordanted/cochineal dyed chicken feathers applying pH 3 and 4 (c,d).

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