Printed in the Republic of Korea
ANALYTICAL SCIENCE & TECHNOLOGY
Vol. 38 No. 5, 340-349, 2025
https://doi.org/10.5806/AST.2025.38.5.340

Pigment characterization of 17th-century Korean large Buddhist hanging scrolls

Ji-Hyeon Yun[1,2], So-Jin Kim[1], and Gyu-Ho Kim[2,★]

[1]*Conservation Science Division, National Research Institute of Cultural Heritage, 132, Munji-ro, Daejeon 34122, South Korea*
[2]*Department of Cultural Heritage Conservation Science, Kongju National University, 56, Gongju-daehak-ro, Gongju 32588, South Korea*
(Received August 13, 2025; Accepted September 15, 2025)

Abstract: Large Buddhist hanging scrolls, known as *Gwaebul* in Korean temples, were produced for outdoor rituals during the late Joseon period. These large-scale paintings have been well preserved due to limited exposure, yet scientific studies remain scarce and often focus on individual works or rely solely on visual examination. Because they are designated as national cultural properties, destructive sampling is restricted, making the use of non-destructive and minimally invasive methods essential. This study examined pigments from three Gwaebul designated as National Treasures: Chiljangsa (1628), Ansimsa (1652), and Sinwonsa (1664). Twenty pigment samples, representing white, yellow, gold, green, blue, and red, were analyzed using digital microscopy, handheld X-ray fluorescence (XRF), and X-ray diffraction (XRD). Lead white was identified in white areas, orpiment in yellow, and gold leaf in gilded regions. Green pigments were copper-based, mainly atacamite; blue pigments were primarily azurite, with occasional niram (dyed calcite); and red pigments consisted mainly of cinnabar, with mixtures of minium in some decorative areas. The results indicate a consistent pigment selection strategy in 17th-century Korean Buddhist paintings, reflecting both material tradition and functional use of color. This study provides a scientific basis for pigment characterization in large-scale heritage paintings and supports future research and conservation of traditional painting materials.

Key words: pigment analysis, Gwaebul, traditional painting materials, X-ray fluorescence, X-ray diffraction

1. Introduction

Buddhist painting in Korea developed after the official adoption of Buddhism in 372 CE, during the Three Kingdoms Period (c. 1st century BCE–668 CE). Early examples through the Unified Silla period (676–935 CE) featured simple color schemes, while the Goryeo Dynasty (918–1392 CE) introduced gold pigment and mineral-based inorganic pigments, leading to a more refined and distinctive color palette.[1-3] During the Joseon Dynasty (1392–1897 CE), although Buddhism faced state-imposed restrictions, *taenghwa*

★ Corresponding author
Phone : +82-(0)41-850-8544 Fax : +82-(0)41-850-8544
E-mail : kimgh@kongju.ac.kr

(framed or scroll paintings on silk or paper) continued to be actively produced. Early Joseon works were stylistically restrained, whereas later paintings featured more vivid coloration and increasingly consistent visual conventions.[1,4,5]

A notable development in the late Joseon period was the creation of large hanging scrolls, known as *Gwaebul*, for outdoor rituals. Some exceed 10 meters in height, and approximately 120 are preserved today.[6-8] Many include *hwa-gi* inscriptions detailing the date, pigments, artists, and patrons, which provide valuable historical information on their production and collaborative nature.[9] Similar large ritual paintings also exist in China (*shuilu*), Japan (*mandala*), and Tibet (*thangka*), but Korean Gwaebul are notable for their scale, vivid coloration, and documentary inscriptions.[10-16]

Due to their size and weight, Gwaebul are rarely displayed and are typically stored in large wooden cases.[17] These conditions, along with their legal status as protected cultural properties, make destructive sampling difficult. As a result, non-destructive and minimally invasive analytical techniques are essential for their study. To address these challenges, a ten-year national survey was conducted in Korea from 2015 to 2024, enabling a range of scientific investigations.[18] While several studies have examined individual Gwaebul or specific colors, comprehensive pigment studies across multiple works remain rare, and few combine both elemental and mineralogical analysis.[19-24]

This study examines the pigment materials used in three 17th-century Gwaebul designated as National Treasures: the Five Buddhas Gwaebul of Chiljangsa Temple (1628), the Vulture Peak Assembly Gwaebul of Ansimsa Temple (1652), and the Vairocana Buddha Gwaebul of Sinwonsa Temple (1664). These works reflect common stylistic features and painting practices of the period. In the field, pigment particles were observed non-destructively using digital microscopy, and elemental compositions were identified using handheld X-ray fluorescence (XRF). Additionally, selected exfoliated micro-samples were brought to the laboratory, where surface-sensitive X-ray diffraction (XRD) analysis was conducted without pulverization. A total of twenty pigment samples, representing six colors (white, yellow, gold, green, blue, and red), were examined. The results aim to provide comprehensive mineralogical and elemental profiles of pigments from large-scale Korean Buddhist paintings, offering a scientific baseline for future comparative studies and conservation strategies.

2. Experimental

2.1. Materials

This study selected pigment samples from the three Gwaebul in six color categories: white, yellow, gold, green, blue, and red. The sample IDs assigned to each painting and pigment color are presented in *Table* 1. The color categories were chosen to represent the major hues used in the paintings and to allow for comparative analysis of pigment composition and mineral structure. Red pigments were commonly obtained from the lips of key figures (C-R, A-R-a, and S-R-a), as these areas often exhibit deliberate color intensification for visual emphasis. Additional samples were collected from other red areas in the Ansimsa and Sinwonsa paintings (A-R-b and S-R-b) to capture tonal differences and assess pigment composition differences based on tonal variation within the same painting.

Fig. 1 presents images of the three paintings, with sample locations annotated to indicate the exact areas of extraction. Twenty samples were collected, primarily from areas where the pigment layer showed signs of flaking, detachment, or instability. Sampling was conducted in consultation with conservators and heritage professionals to ensure that damage to the paintings was minimized. The selected sites were chosen based on both their analytical value and minimal impact on the integrity of the artworks. Each sample was carefully labelled, documented, and stored for subsequent analysis.

2.2. Digital microscopy

Microscopic observations were performed to examine the particle shapes, sizes, and application conditions of the pigments. A handheld digital microscope

Table 1. Analyzed Gwaebul and their pigment samples

Gwaebul	Year	Dimension (cm)	Color	Sample ID
Five Buddhas from Chiljangsa Temple	1628	660 × 399	White	C-W
			Yellow	C-Y
			Gold	C-G
			Green	C-Gr
			Blue	C-B
			Red	C-R
Assembly on Vulture Peak from Ansimsa Temple	1652	866 × 486	White	A-W
			Yellow	A-Y
			Gold	A-G
			Green	A-Gr
			Blue	A-B
			Red	A-R-a
				A-R-b
Vairocana Buddha from Sinwonsa Temple	1664	1083 × 651	White	S-W
			Yellow	S-Y
			Gold	S-G
			Green	S-Gr
			Blue	S-B
			Red	S-R-a
				S-R-b

Fig. 1. Pigment extraction locations in three 17th-century Gwaebul, labelled with sample IDs.

(DG-3x, Scalar Corp., Japan) was used to capture images of the sampled areas at a magnification of approximately 100×. This device allowed non-invasive observation of fine pigment details without the need for sampling, making it particularly useful for visualizing the pigment layers in situ.

In addition to the sampled points, adjacent areas were also examined to understand the overall surface

conditions and assess how the pigments were applied or possibly blended. The high-resolution images obtained with the digital microscope enabled the identification of particle boundaries, distribution patterns, and surface textures, which were essential for interpreting the artists' techniques—such as whether the pigments were applied as single layers or mixtures, or whether overpainting was present. Furthermore, due to its portability and ease of use, the device proved especially suitable for on-site analysis of large-scale artworks such as Gwaebul, where physical access is limited and destructive sampling is minimized.

2.3. X-ray fluorescence (XRF)

Elemental analysis was conducted on-site using a handheld XRF spectrometer (DELTA, Olympus, USA) in a non-destructive manner. The device operated with a voltage of 10~40 kV and a current of 80~200 μA, utilizing an Rh target and a silicon drift detector (SDD). Measurements were obtained in two analytical modes: Geochem mode for 60 seconds and Soil mode for 80 seconds, with a spot size of approximately 15 mm.

These dual-mode settings were selected to maximize the detection range of both light and heavy elements, enabling a more comprehensive elemental profile of the pigments. Geochem mode is optimized for detecting elements such as Pb, As, and Cu, while Soil mode enhances sensitivity to lighter elements including Mg, Al, and Si. The use of both modes provided complementary data that improved the reliability of interpretation.

To ensure the reproducibility and accuracy of the results, the instrument was calibrated on-site by adjusting energy levels, X-ray intensity, and resolution settings. Prior to analysis, the performance of the spectrometer was validated using certified reference materials to confirm measurement stability and accuracy.[25] The non-invasive nature of this technique allowed for precise material characterization on-site without causing damage to the paintings, making it especially suitable for the analysis of valuable and fragile heritage artworks.

2.4. X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis was conducted to identify the mineral phases present in the pigment samples. Selected exfoliated micro-samples were analyzed without pulverization, enabling surface-sensitive detection of crystalline phases while preserving the stratigraphy of the pigment layers. The analysis was performed using an X-ray diffractometer (Empyrean, PANalytical, Netherlands) equipped with a Cu target and a high-resolution Pixel 3D-256ch detector, operating at 45 kV and 40 mA. The angular range (2θ) was scanned from 10° to 70° with a step size of 0.026°, providing sufficient resolution to distinguish fine crystalline phases.

Phase identification was carried out by matching the diffraction patterns with standard mineral references from the International Centre for Diffraction Data (ICDD) database. Each diffractogram was examined to determine the primary and secondary crystalline phases present in the pigments.

To ensure accurate pigment identification, the XRD results were cross-validated with elemental composition data obtained from non-destructive XRF analysis.[25,26] This integrated approach helped compensate for the limitations of individual techniques and enabled a more comprehensive interpretation of pigment composition and crystallinity.

3. Results

3.1. Microscopic observation

Fig. 2 presents digital microscopic images (×100 magnification) of pigment samples from six color groups—white, yellow, gold, green, blue, and red—collected from the three 17th-century Gwaebul. The samples showed variations in particle size, morphology, and distribution within each color group.

White pigment samples (C-W, A-W, S-W) were collected from background cloud motifs (C-W, S-W) and the hair of a central figure (A-W). All three samples displayed densely packed, fine white particles with relatively uniform size and shape. The particles had smooth surfaces and were compactly aggregated.[27]

Yellow pigment samples (C-Y, A-Y, S-Y) were

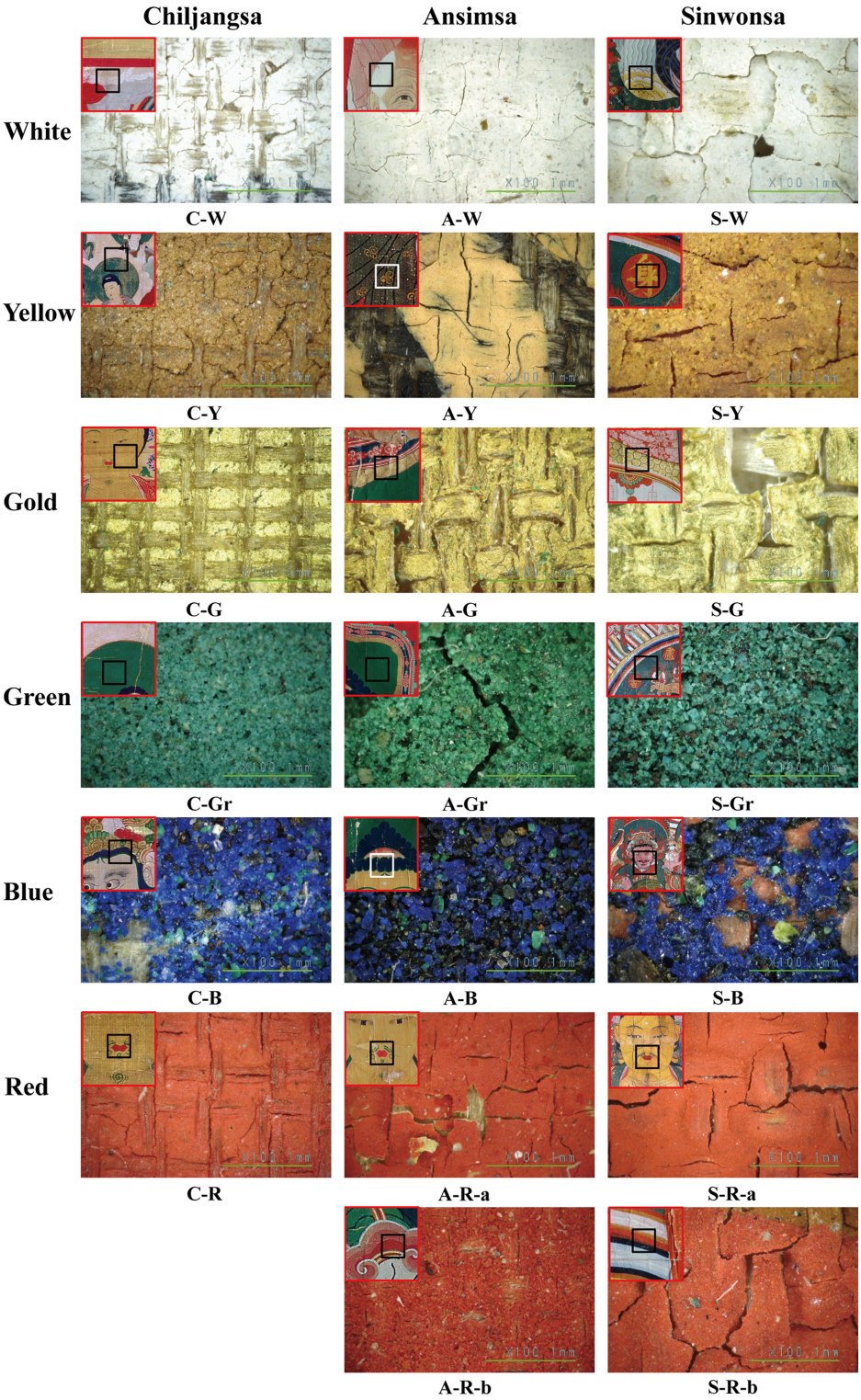

Fig. 2. Digital microscopic images (×100) of pigment samples from the three 17th-century Gwaebul, arranged by color.

obtained from the halo border, garment embellishments, and inscriptions, respectively. C-Y and S-Y contained coarse, irregular particles, whereas A-Y showed finer grains that were more evenly distributed across the surface.

Gold pigment samples (C-G, A-G, S-G) showed metallic, glossy foil-like material applied over a white preparatory layer. This laminated structure was observed in all three samples and appeared consistent across the paintings.[22]

Green pigment samples (C-Gr, A-Gr, S-Gr) were collected from the background area of the halos. These samples contained a mixture of rounded, oval, and angular particles that formed botryoidal aggregates.[27,28]

Blue pigment samples (C-B, A-B, S-B) were taken from the hair (C-B, A-B) and beard (S-B) of the figures. All samples exhibited a combination of blue and green particles, transparent grains, and dark inclusions. In the S-B sample, a red-colored layer was visible beneath the blue layer.

Red pigment samples (C-R, A-R-a, S-R-a) were collected from the lips, and additional red samples (A-R-b, S-R-b) were taken from decorative clouds and background areas. The lip samples consisted of densely agglomerated fine red particles, while the decorative red areas contained coarser red and orange particles in a mixed distribution.

3.2. Elemental analysis

Fig. 3 presents the XRF spectra of pigment samples collected from the three 17th-century Gwaebul, organized by color to facilitate comparison among the six pigment groups. The analysis was conducted to determine the elemental composition of each sample and to compare elemental distributions across different color categories.

White pigment samples (C-W, A-W, S-W) consistently showed high concentrations of lead (Pb) and sulfur (S) (*Fig.* 3a). The S signal was influenced by spectral interference between the Mα emission line of Pb and the Kα line of S, which complicates quantitative interpretation.[29,30]

Yellow pigment samples (C-Y, A-Y, S-Y) exhibited signals for magnesium (Mg), S, silicon (Si), aluminum (Al), and arsenic (As) (*Fig*. 3b). Elevated Mg values were observed in all three samples; however, these may not represent actual Mg content. The Lα line of As overlaps with the Kα line of Mg, particularly when As is abundant, potentially resulting in an overestimation of Mg. Therefore, the detected Mg should be interpreted with caution.[29,30]

Gold pigment samples (C-G, A-G, S-G) contained phosphorus (P), S, As, and gold (Au) (*Fig.* 3c). Multiple spectral overlaps must be considered in interpreting these results. Specifically, the Kβ emission line of P overlaps with the Mα line of Au, and the Kβ line of As overlaps with the Lβ line of Au, complicating the accurate quantification of these elements.[29-30] The detected S likely originated from the underlying white preparatory layer.

Green pigment samples (C-Gr, A-Gr, S-Gr) showed copper (Cu) and chlorine (Cl) as the dominant elements (*Fig.* 3d), with no significant signals from other transition metals.

Blue pigment samples (C-B, A-B, S-B) also showed prominent Cu signals (*Fig*. 3e). In the S-B sample, additional peaks corresponding to Pb and S were observed. These are considered to have originated from the red ground layer of the face, over which the blue lines were painted.

Red pigment samples (C-R, A-R-a, S-R-a, A-R-b, S-R-b) exhibited S, As, and mercury (Hg) (*Fig.* 3f), consistent with the use of Hg-based pigments. Pb was additionally detected in the A-R-b and S-R-b samples. In these cases, the As signal may have been influenced by spectral interference between the Lβ line of Hg and the Kβ line of As, which should be taken into account in interpretation.[29,30]

3.3. Crystalline structure analysis

Fig. 4 presents the XRD patterns of pigment samples collected from the three 17th-century Gwaebul, arranged by color to illustrate the mineralogical composition of each pigment group. Different crystalline phases were identified for each color group, and in several cases, additional minerals or impurities were also detected, indicating complex pigment compositions.

White pigment samples (C-W, A-W, S-W) showed

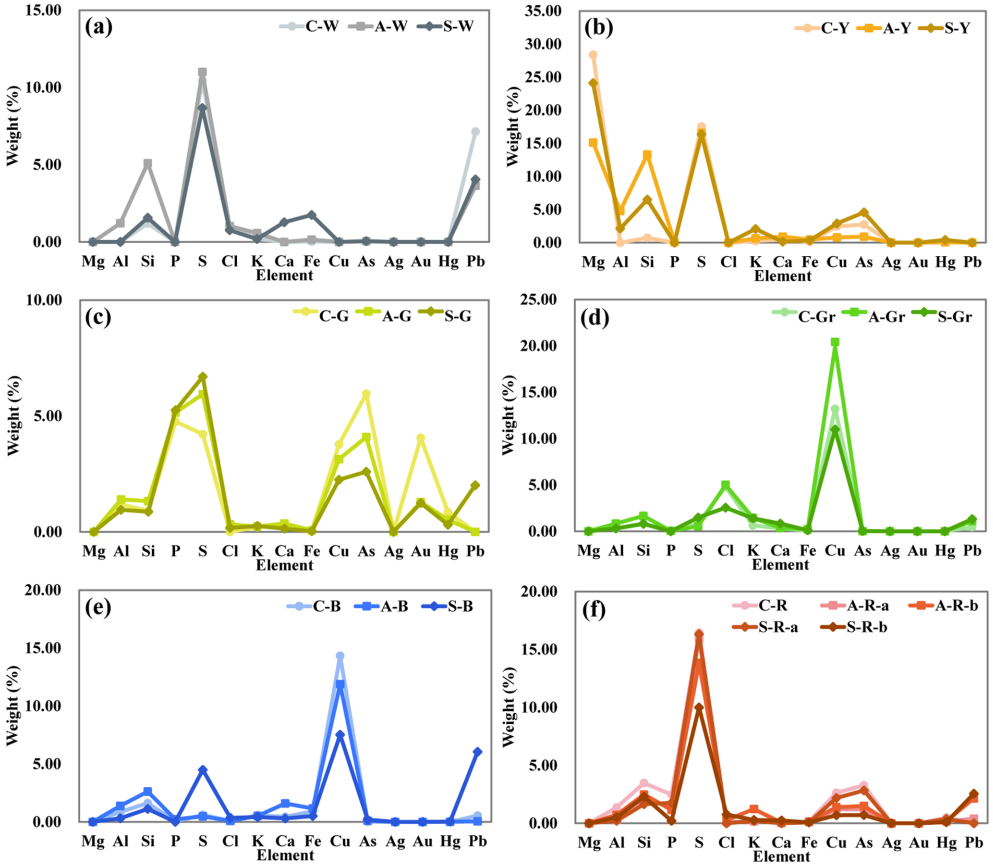

Fig. 3. Comparative XRF spectra of pigment samples from the three 17th-century Gwaebul, arranged by color: (a) white, (b) yellow, (c) gold, (d) green, (e) blue, (f) red.

consistent diffraction peaks corresponding to hydrocerussite [$Pb_3(CO_3)_2(OH)_2$] and cerussite ($PbCO_3$) across all three cases (*Fig.* 4a).

Yellow samples (C-Y, A-Y, S-Y) exhibited peaks for orpiment (As_2S_3) in all cases (*Fig.* 4b). Quartz (SiO_2) was additionally detected in A-Y and S-Y, but not in C-Y.[31]

Gold pigment samples (C-G, A-G, S-G) displayed strong and sharp peaks corresponding to metallic gold (Au), with similar patterns across the three samples (*Fig.* 4c).

Green pigment samples (C-Gr, A-Gr, S-Gr) presented diffraction patterns matching both atacamite and botallackite [$Cu_2(OH)_3Cl$], which coexisted in all three samples (*Fig.* 4d).

Blue samples (C-B, A-B, S-B) showed azurite [$Cu_3(CO_3)_2(OH)_2$] as the main phase (*Fig.* 4e). Additional peaks for calcite ($CaCO_3$) and quartz were observed in A-B and S-B, respectively.

Red samples (C-R, A-R-a, S-R-a, A-R-b, S-R-b) consistently exhibited cinnabar (HgS) across all cases (*Fig.* 4f). Minium (Pb_3O_4) was additionally identified in A-R-b and S-R-b.

4. Discussion

This study examined pigments in 17th-century Korean Gwaebul paintings through an integrated approach combining microscopic observation, elemental analysis, and crystalline phase identification. Six color groups were analyzed to determine their composition, particle characteristics, and application patterns.

White pigments, applied to cloud motifs and outlines, contained Pb, with hydrocerussite and cerussite

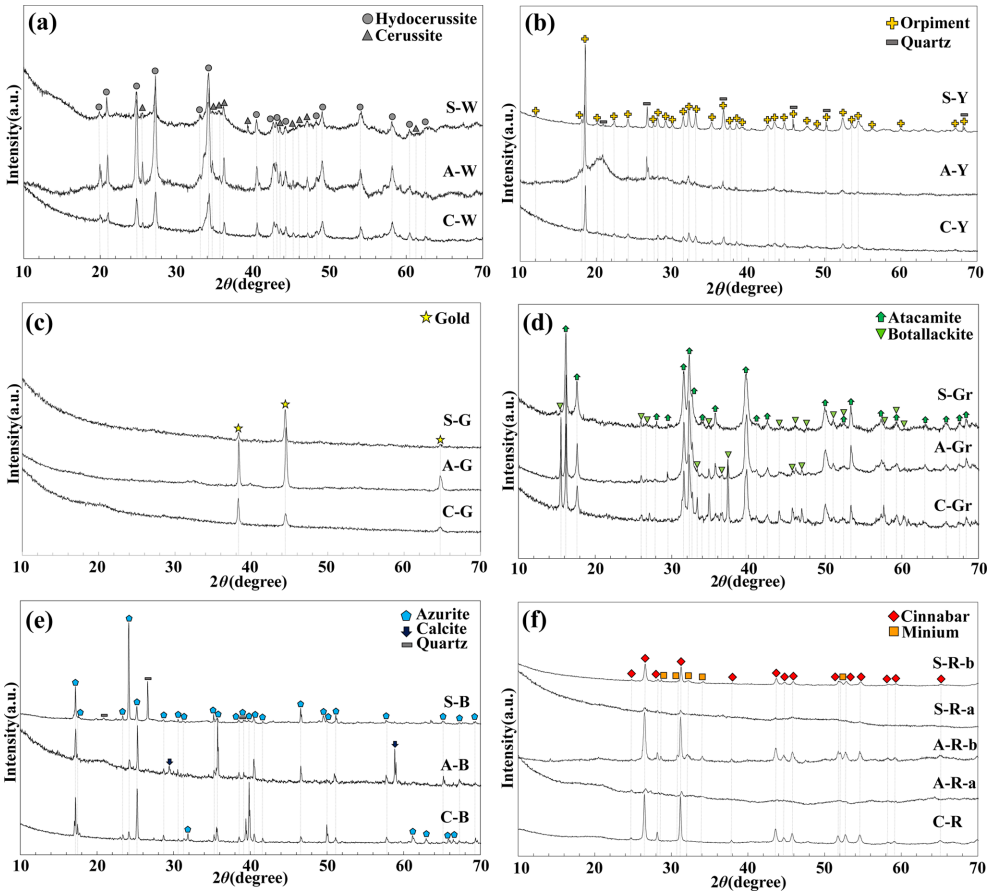

Fig. 4. XRD patterns of pigment samples from the three 17th-century Gwaebul, arranged by color: (a) white, (b) yellow, (c) gold, (d) green, (e) blue, (f) red.

identified as the principal phases. The fine, densely packed particles of lead white were well suited for uniform application and precise linear definition.

Yellow pigments, used in detailed decorative elements to enhance color contrast, exhibited As and S in elemental spectra, with orpiment identified as the main phase. Differences in particle morphology among samples suggest variations in pigment refinement or application techniques.

Gold was applied to decorative motifs and selected iconographic components, serving both visual and symbolic purposes through the reflective quality of metal leaf. Au was confirmed in all three paintings, where gold leaf was consistently applied over a lead white ground. This technique reflects a broader late Joseon trend toward increased gilding, in contrast to earlier Goryeo paintings, which predominantly employed powdered gold pigment.[3]

Green pigments, found in halos and backgrounds, contained Cu and Cl, with atacamite and botallackite identified. These pigments exhibited botryoidal aggregates with diverse particle shapes, suggesting favorable material properties for stable and uniform application.[27,28]

Blue pigments consisted mainly of azurite, with occasional admixtures of niram (indigo). These were used for hair and beards, and in some cases applied over red layers to deepen tone and enhance chromatic contrast.

Red pigments varied notably by location: cinnabar was used exclusively for lips, while mixtures with minium appeared in decorative backgrounds. Variations

in particle size and composition across application areas suggest deliberate adjustments for visual effect.

5. Conclusions

This study analyzed pigments in three 17th-century Korean Gwaebul paintings using digital microscopy, handheld X-ray fluorescence, and laboratory-based X-ray diffraction. The results show that pigment selection and painting techniques were adapted to meet the visual, symbolic, and technical requirements of late Joseon Buddhist works.

Traditional inorganic pigments were consistently identified, with evidence of adjustments in refinement, layering, and spatial application to enhance color contrast and visual emphasis. The identification of both atacamite and botallackite in green areas highlights the value of crystalline phase analysis in distinguishing closely related mineral phases.

The combined application of non-invasive in-situ XRF and laboratory-based XRD provided a reliable framework for pigment identification in large-scale, immovable heritage paintings, offering a methodology applicable to the study and conservation of other similarly painted cultural heritage objects.

Acknowledgements

This study was supported by the Cultural Heritage Research and Development (R&D) project (NRICH-2505-A79F-1) of the National Research Institute of Cultural Heritage of the Korea Heritage Service, Daejeon, South Korea. This research was also supported by the National University Development Project of the Ministry of Education, Korea in 2023. We are grateful to the Research Institute of Sungbo Cultural Heritage for providing photographs of the paintings used in this study.

References

1. M. D. Moon, ‘History of Korean Buddhist Painting’, Dahal Media, Seoul, 2021.
2. C. S. Park, *Dongak Art Hist.*, **15**, 327-350 (2013). https://doi.org/10.17300/jodah.2013..15.012
3. M. Kim, *J. Seokdang Acad.*, **73**, 55-84 (2019). https://doi.org/10.17842/jsa.2019..73.55
4. J. H. Kim, *J. Buddhist Art*, **5**, 325-351 (2007). https://academic.naver.com/article.naver?doc_id=45429181
5. H. G. Kwon, ‘A Study on the Characters of the Changes of Buddhist Paintings in the Late Chosun Dynasty’ Master’s thesis, Hongik University, Seoul, 2008.
6. Y. S. Lee, ‘Study on Gwaebultaeng during the latter period of Joseon Dynasty’ Ph.D. Dissertation, Dongguk University, Seoul, 2004.
7. M. H. Chung, ‘A Study on the Gaebul painting of the late Chosun Dynasty’ Master’s thesis, Hongik University, Seoul, 2001.
8. J. H. Kim, In ‘The Origin and Production Background of Gwaebul’, The Beauty of Korean Gwaebul 1: Gyeongsang-Do Province, National Research Institute of Cultural Heritage, Daejeon, 2022.
9. M. H. Jeong, *J. Korean Art Archaeol.*, **17**, 12-30 (2023). https://doi.org/10.23158/jkaa.2023.v17_02
10. P. E. Bloom, ‘Descent of the Deities: The Water-Land Retreat and the Transformation of the Visual Culture of Song-Dynasty (960-1279) Buddhism’ Ph.D. Dissertation, Harvard University, Cambridge, 2013.
11. M. Chusid, *Ars Orient.*, **54**, 79-107 (2024). https://doi.org/10.3998/ars.7031
12. R. Wen and F. Fan, *J. Cult. Herit.*, **40**, 120-133 (2024). https://doi.org/10.1016/j.culher.2024.08.020
13. S. Wang and F. Fan, *Remote Sens.*, **15**, 3603, 1-17 (2023). https://doi.org/10.3390/rs15143603
14. J. B. N. Loh, *J. Conserv. Mus. Stud.*, **8**, 1-19 (2002). https://doi.org/10.5334/jcms.8021
15. Y. S. Yun, ‘Gwaebul’, Daewonsa, Paju, 1995.
16. E. W. Lee, J. H. Yoon, Y. M. Kwon, and T. H. Shin, *J. Conserv. Sci.*, **36**(6), 519-532 (2020). https://doi.org/10.12654/JCS.2020.36.6.08
17. S. H. Her, *J. Buddhist Art*, **28**, 757-792 (2019). https://doi.org/10.36620/BMS.2019.28.30
18. Korea Heritage Service, ‘Large Buddhist Painting Conservation Processing Guide Book’, Korea Heritage Service, Daejeon, 2024.
19. J. J. Lee, J. Y. Ahn, Y. M. Yoo, K. M. Lee, and M. S. Han, *J. Conserv. Sci.*, **33**(6), 431-442 (2017). https://doi.org/10.12654/JCS.2017.33.6.03

20. E. W. Lee, Y. J. Gyeong, J. H. Yun, Y. M. Kwon, J. W. Song, M. S. Seo, and J. J. Lee, *J. Conserv. Sci.*, **35**(6), 689-700 (2019). https://doi.org/10.12654/JCS.2019.35.6.12
21. J. H. Yun, S. J. Kim, and G. H. Kim, *Korean J. Cult. Herit. Stud.*, **55**(3), 120-129 (2022). https://doi.org/10.22755/kjchs.2022.55.3.120
22. N. R. Lee, J. H. Yun, and S. J. Kim, *J. Raman Spectrosc.*, **54**(8), 836-846 (2023). https://doi.org/10.1002/jrs.6565
23. N. R. Lee, Y. M. Yoo, and S. J. Kim, *Korean J. Cult. Herit. Stud.*, **56**(4), 216-228 (2023). https://doi.org/10.22755/kjchs.2023.56.4.216
24. N. R. Lee, S. J. Kim, and K. S. Han, *Korean J. Herit. Hist. Sci.*, **58**(1), 62-80 (2025). https://doi.org/10.22755/kjchs.2025.58.1.62
25. Y. N. Song, 'Materials Characteristics of Pigments on Dancheong in Joseon Dynasty' Ph.D. Dissertation, Kongju National University, Gongju, 2018.
26. D. H. Moon, M. S. Han, H. Y. Jeong, I. H. Go, and H. G. Cho, *J. Conserv. Sci.*, **32**(3), 403-415 (2016). https://doi.org/10.12654/JCS.2016.32.3.11
27. N. Eastaugh, V. Walsh, T. Chaplin, and R. Siddall, 'Pigment Compendium: Optical Microscopy of Historical Pigments', Routledge, London, 2004.
28. Y. S. Kang, J. H. Park, S. W. Mun, G. H. Hwang, M. N. Kim, and S. M. Lee, *Korean J. Cult. Herit. Stud.*, **56**(2), 148-169 (2023). https://doi.org/10.22755/kjchs.2023.56.2.148
29. A. Bezur, L. Lee, M. Loubser, and K. Tretelman, 'Handheld XRF in Cultural Heritage: A Practical Workbook for Conservators', Getty Conservation Institute, Los Angeles, 2012.
30. R. Jenkins, 'X-ray Fluorescence Spectrometry', 2nd Ed., Wiley-Interscience, New York, 1999.
31. J. J. Lee, Y. J. Gyeong, J. S. Lee, and M. S. Seo, *Korean J. Cult. Herit. Stud.*, **52**(4), 226-245 (2019). https://doi.org/10.22755/kjchs.2019.52.4.226
32. J. S. Oh, S. R. Lee, and M. Y. Hwang, *Korean J. Cult. Herit. Stud.*, **53**(2), 64-87 (2020). https://doi.org/10.22755/kjchs.2020.53.2.64
33. J. Y. Do and J. M. Jung, *J. Mineral. Petrol.*, **31**(2), 123-135 (2018). https://doi.org/10.9727/jmsk.2018.31.2.123
34. I. H. Go and T. H. Choi, *J. Korea TAPPI*, **48**(3), 57-65 (2016). https://doi.org/10.7584/ktappi.2016.48.3.057
35. C. Cardell, A. Herrera, I. Guerra, N. Navas, L. R. Simon, and K. Elert, *Dyes Pigments*, **141**, 53-65 (2017). https://doi.org/10.1016/j.dyepig.2017.02.001
36. M. Aru, L. Burgio, and M. S. Rumsey, *J. Raman Spectrosc.*, **45**(11-12), 1013-1018 (2014). https://doi.org/10.1002/jrs.4469
37. S. S. Pawełkowicz, B. Wagner, J. Kotowsk, G. Z. Zukowska, B. Golebiowska, R. Siuda, and P. Jokubauskas, *Minerals*, **11**, 1236, 1-22 (2021). https://doi.org/10.3390/min11111236