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Bibliometric analysis of knowledge structures and evolution in global painting art from 1994 to 2024

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This study examines 5457 Web of Science publications (1994–2024) to map the development of global painting art research. Using a newly designed bibliometric framework (PDU) and knowledge visualization, it reveals patterns of knowledge distribution, collaborative structures, major research themes, and evolutionary shifts from material analysis toward multi-layered diagnostic and micro-analytical approaches, underscoring the role of cross-disciplinary integration in shaping methodological and interpretive developments.

Painting is a material and embodied practice. It involves the use of different tools charged with pigment to make gestural marks on a surface, where physical action and visual form come together. Beyond what is represented, painting reveals the painter's style of seeing and interpreting the world, offering a unique way of expressing human experience through bodily movement and esthetic space[1]. From the ritualistic depictions of Paleolithic cave paintings to the conceptual explorations within the contemporary "expanded field," painting has continuously pushed the boundaries of its medium, undergoing paradigmatic shifts[2]. As its forms, functions, and discourses have changed, the definition of painting art has remained open to debate. Clement Greenberg emphasized flatness and medium specificity as its essential conditions[3], whereas Arthur Danto argued that its status as art depends on the concepts and theoretical frameworks that place it within the artworld[4]. With the expansion of artistic practices across material, digital, and conceptual domains, painting art now exceeds any single criterion and cannot be reduced to medium, representation, or visual form alone. In this study, painting art is defined as a practice in which pigment-based or pigment-referential mark making, whether produced materially, digitally, or conceptually, serves as a means of constructing images, shaping perception, and generating cultural meaning.

Throughout history, the study of painting has undergone several paradigm shifts. Its institutional foundations were laid during the Renaissance[5] and consolidated through the professionalization of art history in the 19th and 20th centuries[6,7] Since then, painting studies have largely revolved around two complementary modes: formal analysis, which examines stylistic development and compositional structure, and contextual interpretation, which situates artworks within broader social, political, and cultural frameworks. By the 1970s, the emergence of "new perspectives" further advanced art-historical inquiry by incorporating critical theory, cultural studies, and anthropology, thereby expanding the discipline's methodological ambitions. Over the past three decades, the field has continued to shift, with Digital Art History and Technical Art History emerging as two particularly prominent new directions. Digital Art History has emerged as one of the most visible new directions, and its rise has sparked substantial debate. From Drucker's seminal question *Is There a Digital Art History?* [8] to Bishop's critique in *Against Digital Art History*[9] and Wasielewski's *Computational Formalism*[10], scholars continue to discuss whether computational methods can supplement or potentially displace the deep contextual and interpretive expertise foundational to art history. Despite these debates, digital approaches have developed rapidly in practice, focusing on the reconstruction of lost or fragmentary contexts through three-dimensional modeling, the large-scale analysis of image corpora, and the quantitative mapping of social, material, and spatial relations in art production[11].

In contrast, Technical Art History foregrounds materials, techniques, and artistic processes, integrating scientific and humanistic approaches. While overlap occurs when material data are computationally analyzed[10], its intellectual trajectory is distinct. The modern form of the field can be traced to the mid-twentieth century, when Edward Waldo Forbes established the first dedicated technical research laboratory at the Fogg Museum at Harvard[12]. The concept of "technical art history" was not formally articulated until the 1990s, when David Bomford defined it as the systematic study of material and documentary evidence to illuminate an artwork's invention, development, elaboration, and revision[13]. Since then, the field has expanded through advances in imaging and analytical science, enabling increasingly refined examinations of pigments, binding media, varnishes, and layer structures. More recent computational tools now assist in recognizing material patterns and reconstructing artistic processes from complex datasets, further strengthening the field's interpretive capacity.

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It is within this context that the very definition of "painting art research" demands reconsideration. Traditionally confined to the humanistic study of painting art within art history, the field now encompasses a wider array of practices. Painting research should therefore be understood more broadly, not only as stylistic and iconographic inquiry but also as work informed by archeology, anthropology, psychology, and esthetics, together with scientific methods for material analysis, authentication, and visualization. To capture this paradigm shift, it is necessary to examine a period in which these developments became particularly salient. Accordingly, this study examines the period from 1994 to 2024, a critical phase in the merging of traditional, technical, and digital approaches in painting research. Given these significant changes over the past three decades, it becomes increasingly important to systematically analyze how the knowledge structure of painting research has developed.

However, traditional qualitative studies, while offering rich contextual insights, may fail to reveal implicit associations and large-scale patterns across broad bodies of literature. Bibliometric analysis provides a promising alternative. Alan Pritchard introduced the term bibliometrics in 1969, who defined it as "the application of mathematical and statistical methods to books and other media of communication" [14]. By applying quantitative methods to track global scholarly output, including publication trends, collaboration networks and keyword dynamics, this approach helps researchers map the development of the field, identify gaps, and refine future research agendas[15]. Although long underutilized in the arts and humanities, bibliometric tools have proven valuable in areas like digital humanities and cultural conservation, which demonstrate how quantitative analysis can clarify research patterns and complement interpretation[16–18].

With an emphasis on documents published between 1994 and 2024, this study aims to systematically address the following questions using bibliometric methods:

Q1: What are the distributional characteristics of knowledge in global painting research?

Q2: Considering the relationships among different knowledge elements, what structural patterns can be observed in the field of painting research?

Q3: From a temporal perspective, are there specific development paths in the field of painting art?

Answering these questions will clarify the direction of painting research and guide its development in the modern academic landscape.

Methods

Overall research framework

A bibliometric-based analysis process was designed to study the global development of the painting research, as shown in Fig. 1. The process is divided into four steps: the first step, "data source selection," involves acquiring an initial collection of scientific documents related to painting; the second step, "dataset construction," aims to generate a cleaned dataset closely associated with painting art; the third step, "analysis methods, indicators, and tools," specifies the dimensions, variables, indicators, and application scopes of the relevant tools for quantitative analysis, and integrates them into a systematic analytical taxonomy called PDU ("Perspective-Dimension-Unit"); the final step, "empirical analysis," produces quantitative results based on the PDU framework and provides further presentation and interpretation of knowledge-related, structural, and evolutionary patterns.

Data source selection

The choice of data source is a critical consideration in bibliometric research[19–21]. This study adopts the Web of Science (WoS) Core Collection as its primary source, due to its rigorous quality control and comprehensive coverage of over 20,000 high-impact journals across the sciences, social sciences, arts, and humanities. Its citation network, traceable back to 1900, provides a robust foundation for analyzing knowledge connections within painting research. To comprehensively capture publications related to painting studies, a topic search strategy was employed using a Boolean query combining major subject terms: TS = ("paint*" OR "pictorial art*" OR "visual expression*" OR "fresco*" OR "mural*" OR "canvas art*" OR "ink wash*" OR "portraiture*"). This formulation aims to include diverse forms of painting scholarship and reduce the omission of interdisciplinary or indirectly related works[22]. The search was conducted across SCI-EXPANDED, SSCI, and A&HCI databases, covering the period from 1994 to 2024, with the document type limited to "Article" and the language to "English." This yielded an initial result set of 32,679 records.

To accurately establish the painting-oriented dataset, a regular workflow was implemented, consisting of two steps: multi-expert journal refinement and document filtering. To exclude documents unrelated to painting art, several domain experts were invited in the relevant field to screen the target journals in an initial journal list containing the abovementioned document collection. The selection criteria mainly contain three aspects: firstly, a typical traditional journal frequently involved in academic research of painting art can be included, such as *Art History*, *The Art Bulletin*, and *Artibus et Historiae*. Secondly, those journals whose disciplines are closely related (e.g. *Journal of Cultural Heritage*, *Archaeometry*, and *Rock Art Research*) can be also incorporated to this filtered collection to ensure the multidisciplinary nature. The third is the requirement of professionalism and authority of individual journal, which prioritizes the selection of journals with high impact factors and authority in the field. Table 1 shows the final journal list with 47 journals after multiple discussions and expert refinement. After manual verification to remove duplicates, the dataset was reduced to 5457 records, representing ~16.7% of the original corpus.

Analytical units, metric and tool

This study integrated the most common indicators and variables in previous bibliometric research and designed a bibliometric-based analytical taxonomy, namely "Perspective-Dimension-Unit" (i.e. PDU) as shown in Fig. 1 and Table 2. It is structured into three complementary perspectives to capture different facets of painting research.

On the one hand, for the content of PDU, the distribution perspective primarily analyses the characteristic distribution of different types of knowledge elements mainly through frequency statistics. It contains the overall research trend analysis based on annual publication and the descriptive statistics of knowledge elements (e.g. countries, institutions, disciplines and journals), thus providing the most basic characteristic information in this field. In contrast, the structural perspective focuses on the exploration of the interactions among various knowledge elements and the structural characteristics reflected by them, which further deepens the understanding of the "relationships" between knowledge elements in the field, such as author collaboration networks, keyword co-word clustering, etc. Finally, from an evolutionary perspective, partitioning independent knowledge landscapes based on time intervals and dynamically identifying the connections and evolutionary paths between topic knowledge can provide us more diverse perspectives by dynamically analyzing the research progress, which is particularly crucial for the discovery of the development venation.

On the other hand, considering the differences in characteristics across these layers, it is clear that the first two perspectives describe the static attributes at different levels of knowledge granularity, while the evolutionary perspective captures the dynamic patterns in the field of painting art. These perspectives are complementary and together provide support for a comprehensive and systematic analysis of the field's research frontiers and historical development.

Based on the characteristics of the dimensions and units analyzed in PDU, different measurement indicators were proposed corresponding to the relevant variables. For publication output and representative carriers, frequency statistics are used to measure the variations for yearly research productivity or to rank representative examples and identify their distribution characteristics. As mentioned earlier, the common feature of the analytical units from a structural perspective is the identification of relationships in the knowledge network. These relations can be shown by the co-

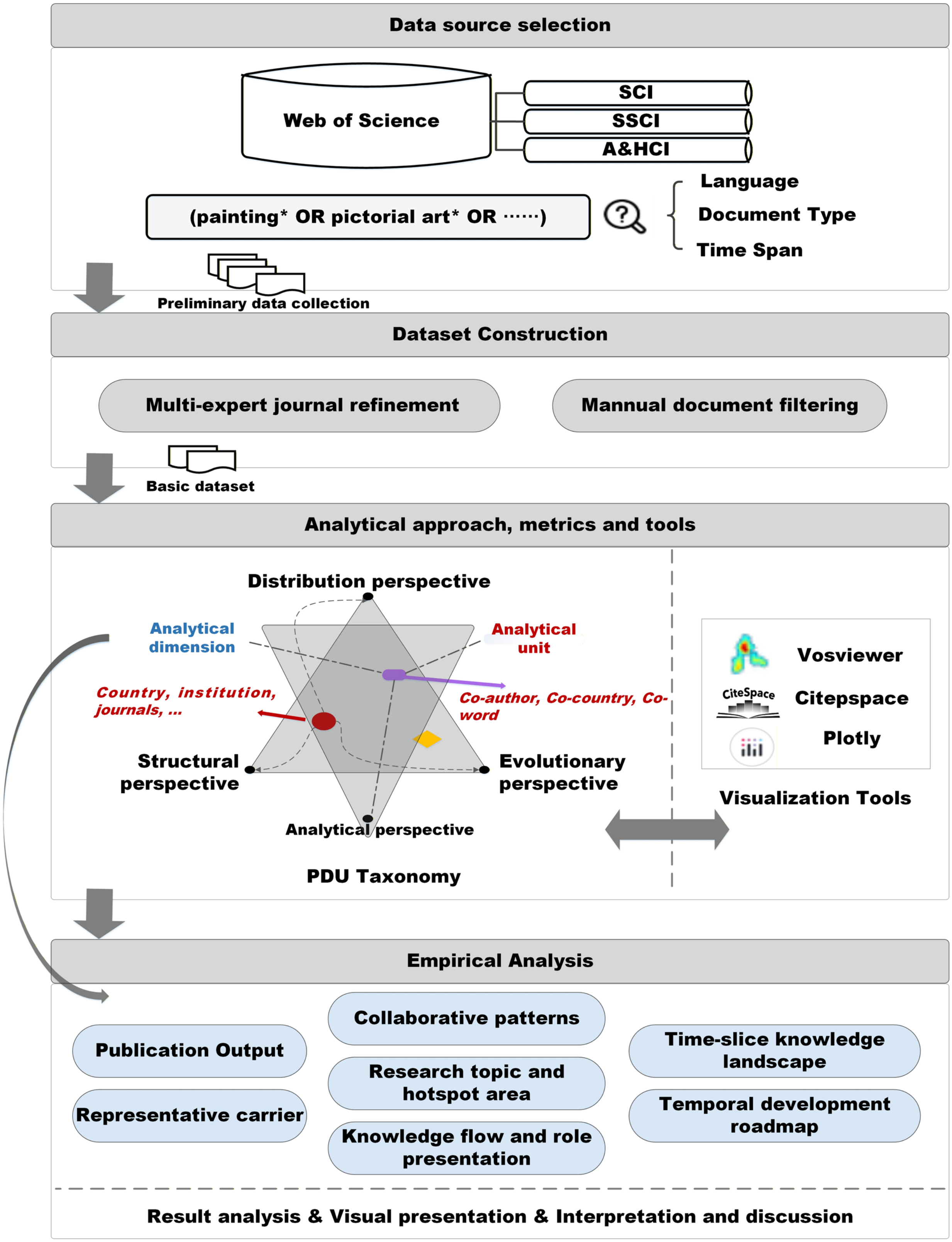

Fig. 1 | Overview of the research workflow and analysis procedure. Source: Authors' own compilation.

citation frequency between research papers, indicating the strength of sharing associated research themes[23]. Also, this metric is regarded as the main representation of knowledge transfer between research frontiers[24,25] (i.e. the current domain development) and knowledge bases[26,27] (i.e. the document support sustaining its research status). Peculiarly, for those "pivot nodes" [28], they often play an indispensable role in the knowledge flow. The roles of these nodes can be described and characterized using centrality-based metrics[29]. Sometimes the influence of these nodes may also be reflected through the burstiness[30] of the key words they contain, that is, the accumulation of positive intensity surges in the yearly sequence of articles,

Table 1 | Selected journals and their primary disciplinary affiliations

Journal title	Primary discipline
Art History	Art History
The Burlington Magazine	Art History
Artibus et Historiae	Art History
The Art Bulletin	Art History
ARTnews	Art History/Art Criticism
Art in America	Art History/Art Criticism
Oxford Art Journal	Art History/Visual Culture
Apollo: The International Magazine of the Arts	Art History/Art Market
The Magazine Antiques	Art History/Decorative Arts
American Art	Art History/American Studies
Umeni (Art)	Art History/Central European Studies
Konsthistorisk tidskrift	Art History/Nordic Studies
Zeitschrift für Kunstgeschichte	Art History/German Studies
Renaissance Quarterly	Art History/Early Modern Studies
Studies in the History of Art	Art History
Source: Notes in the History of Art	Art History
Archives of Asian Art	Art History/Asian Studies
Gesta	Medieval Art History
Simiolus: Netherlands Quarterly for the History of Art	Art History
Art Journal	Art History/Art Criticism
Art Criticism	Art Criticism
Visual Studies	Visual Culture/Media Studies
Religion and the Arts	Religious Studies/Art History
Chinese Literature	Literary Studies/Visual Culture
Journal of Cultural Heritage	Heritage Science
Studies in Conservation	Conservation Science
Heritage Science	Heritage Science
Heritage	Heritage Science
Microchemical Journal	Analytical Chemistry/Heritage Science
Analytical and Bioanalytical Chemistry	Analytical Chemistry/Heritage Science
Journal of Raman Spectroscopy	Spectroscopy/Heritage Analysis
Analytica Chimica Acta	Analytical Chemistry
Radiation Physics and Chemistry	Physical Chemistry/Material Analysis
Dyes and Pigments	Material Science/Pigment Studies
Archaeometry	Archeological Science
Journal of Archeological Science	Archeological Science
Journal of Archeological Science: Reports	Archeological Science
Mediterranean Archeology and Archaeometry	Archaeometry/Regional Archeology
Rock Art Research	Archeology/Visual Culture
Archeological and Anthropological Sciences	Archeology/Anthropology
Antiquity	Archeology
Southern African Humanities	Archeology/Anthropology
Journal of the History of Collections	Museum Studies/Provenance Research
Religions	Religious Studies
Psychology of Esthetics, Creativity, and the Arts	Psychology/Esthetics
Empirical Studies of the Arts	Cognitive Science/Esthetics
The Journal of Esthetics and Art Criticism	Philosophy/Esthetics

Source: Journals included in the painting art research dataset (1994–2024) after multi-expert refinement and document filtering.

Table 2 | The taxonomy of PDU

Analytical perspective	Analytical dimension	Analytical units
Distribution perspective	Publication output	Yearly publication
	Representative carrier	Representative countries
		Core institutions
		Discipline categories
		Productive journals
Structural perspective	Collaborative patterns	Co-country/institution/author network
	Research topic and hotspot area	Co-word Clustering
	Knowledge flow and role presentation	Co-citation linkage and crucial paper
Evolutionary perspective	Time-slice knowledge landscape	Topic subnetwork
	Temporal development roadmap	Topic dissemination path

Source: Developed for the present study to structure publication, collaboration, and evolution analysis in painting art research.

which can implicitly indicate the potential innovation and breakthrough progress that those articles may have. In addition, co-authorship networks and co-word analysis are two typical approaches to recognize the structure patterns[31,32], which view the relationship of "co-occurrence" as a prerequisite for structural analysis. The keyword co-occurrence networks in co-word analysis has become an important means to reveal the academic semantic structure. It constructs a network through the co-occurrence frequency of keywords and demonstrates cumulative knowledge and meaningful knowledge components of the research field. In the co-word network, due to the potential research bias generated by the semantic relevance of keywords, clustering analysis can be further employed to revealing the structured topic groups composed of high-frequency keywords. These clustered topics enable a macroscopic display of the distribution of current research hotspots, which are often regarded as the potential wind vane of the "research direction". Considering the dynamic development of the field of painting art, it is possible to segment it to multiple sub-networks at a time scale and use relevant indicators to characterize its local stages. These indicators can be measured using various general measurement commonly used in network science[33–35], such as network diameter, average degree, average path length, density, average clustering coefficient, as well as modularity and number of clusters obtained from community detection-based clustering. Similarly, after constructing knowledge clusters for each subnet, the similarity between topic clusters at different stages can be calculated to obtain a stage-based development path and identify the crucial progress for the transmission of painting art knowledge. A summary of the key structural metrics and co-occurrence-based calculations employed in this study is provided in Table 3.

Table 3 | Analytical metrics for structural network and co-occurrence analysis

Metric	Key formula	Illustration
Degree centrality	$DC_i = \sum_{j \in U(i)} I_{i,j}(j \neq i)$	Identification of those pivot node i based on the "star effect", with the assumption of an indicator function as $I_{i,j}(\cdot)$ ($I_{i,j} = 1$ only when there a direct edge linking node i to node j, else $I_{i,j} = 0$) and the neighbor node sets of i as $U(i)$
Betweeness centrality	$BC_i = \sum_{s \neq i, i \neq j, s<j} \frac{\sum_{s \to i \to j} I_{s,j}(s \neq j)}{\sum_{s \to j} I_{s,j}(s \neq j)}$	Identification of those pivot node i based on the "bridge effect", with the assumption of an indicator function as $I_{s,j}(\cdot)$ same to the above. Note that $s \to i \to j$ means all the paths from j to s through i
Co-occurrence strength	$C_{i,j} = \frac{F_i \cdot F_j}{F_{i,j}}$	Measuring the linking strength for the relationship between any pair of knowledge nodes, with the assumption of the paper occurrence of i as F_i, and the paper co-occurrence of i and j as $F_{i,j}$.
Maximum co-citation Interval	$MCI = \max_{t_{i,co} \in [T, T+\Delta T]} t_{i,co}$	measuring the longest time interval of co-cited papers in the timepoint range of T to $T + \Delta T$
Network diameter	$D = \max_{p \in [1,P]} d_p$	Calculation of the maximum value of all distances.
Average path length	$AAL = \frac{1}{P} \sum_{p=1}^{P} d_p$	Calculation of the mean value of all distances (e.g. a distance denoted as d_p).
Density	$D_{density} = \frac{2m}{N \cdot (N-1)}$	Measuring the ratio of the actual total number of edges to the number of edges in its fully connected graph, supposing that m is the total number of edge and N is the total number of nodes.
Average clustering coefficient	$ACC = \frac{1}{I} \sum_{i=1}^{I} \frac{2e_i}{DC_i \cdot (DC_i - 1)}$	Describing the clustering degree between vertices in a graph whose size is I, which is obtained based on the degree to which adjacent nodes of a node are connected to each other. Note that e_i is the number of the connections between all neighbors of node i.
Modularity	$Q = \frac{1}{2m} \sum_{i,j} \left(A_{i,j} - \frac{DC_i \cdot DC_j}{2m} \right) \cdot \delta_{i,j}$	measuring the tightness of nodes within each cluster, which is regarded as the most commonly used evaluation indicator for evaluating the effectiveness of community detection-based clustering, with the assumption of an indicator function as $\delta_{i,j}$ ($\delta_{i,j} = 1$ only when node i and node j belong to the same cluster, else $\delta_{i,j} = 0$), the total number of edge m, and an adjacent matrix $A_{i,j}$ for all nodes.

Source: Developed for the present study to define network metrics used in structural and co-occurrence analysis of painting art research.

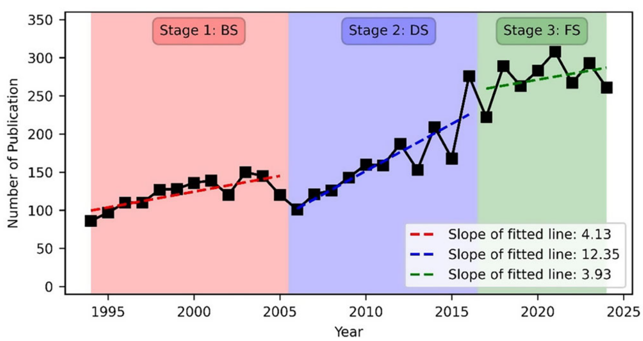

Fig. 2 | Yearly publication output in painting art research (1994–2024) with fitted lines based on the Ordinary Least Squares (OLS). Source: Web of Science (Core Collection).

To support the structural analysis, we also apply three visualization tools. VOSviewer (v1.6.20), developed by Van Eck and Waltman[36,37], generates high-quality visualizations of collaboration networks (e.g. co-author ones, co-country ones or co-institutions), citation networks (e.g. document-oriented, and journal-oriented), and keyword co-occurrence networks, revealing research structures and thematic linkages. CiteSpace-II, another key tool, which can detect and visualize emerging trends and transient patterns in scientific records[38]. This tool helps us observe structural changes in domain knowledge and highlights key nodes in the field of painting art, offering a broader view of the knowledge landscape. Finally, Plotly, a Python-based interactive tool, enables temporal visualization of thematic clusters and their dynamic evolution, helping construct an evolutionary path map of painting research.

Results

Knowledge distribution

The annual publication output of painting research from 1994 to 2024 is shown in Fig. 2. Over the past three decades, the field has exhibited a steady upward trajectory, with total publications increasing more than threefold despite periodic fluctuations. Based on the overall trend, this 30-year period can be divided into three distinct stages. The Blooming Stage (BS, 1994–2006) is characterized by a general upward trend accompanied by noticeable year-to-year fluctuations. Annual publications increased from 86 in 1994 to a mid-stage peak of 150 in 2003, before declining to 101 in 2006. Despite these oscillations, the fitted slope of 4.13 indicates moderate yet consistent expansion as painting studies gained wider visibility across academic and conservation contexts. The Development Stage (DS, 2006–2016) is characterized by accelerated output and increased volatility. Annual publications fluctuated between 120 and 209, while the fitted slope rose to 12.35, suggesting a phase of intensified research activity and thematic diversification within the field. The Flourishing Stage (FS, 2016–2024) demonstrates a period of sustained high productivity, with outputs consistently exceeding 200 publications per year and reaching a peak of 308 in 2021. Although the fitted slope slightly declined to 3.93, the overall volume remained high, reflecting a stage of structural maturity and stable research output in painting studies.

Beyond temporal trends, its global configuration offers another perspective on the field's development. Global painting arts research demonstrates a simultaneous pattern of concentration and diversification across national, institutional, disciplinary, publication and author dimensions, as shown in Table 4.

Geographical concentration emerges as a salient pattern in global painting research, revealing an uneven distribution of academic productivity across regions. The United States leads the field, accounting for approximately one quarter of all publications. Italy and England follow as major European centers, while Spain and China constitute a secondary group of productive countries. France, the Netherlands, Germany, Australia, and Belgium also make notable contributions, further confirming Europe's sustained dominance in the discipline. By contrast, Africa, South and Southeast Asia, and Latin America remain underrepresented, revealing persistent regional disparities in global painting research.

Institutionally, painting research remains geographically concentrated, with Europe retaining clear leadership in both productivity and institutional presence. Italy's Consiglio Nazionale delle Ricerche (CNR) stands out as the most productive institution worldwide, followed by France's Centre National de la Recherche Scientifique (CNRS), the University of London, and the University of Florence. North American institutions hold a similarly

Table 4 | Knowledge carrier distribution in painting art research

Top 10 productive countries				Top 10 productive institutions			
Rank	Country	Counts	Proportion (%)	Rank	Institution	Counts	Proportion (%)
1	USA	1320	24.19	1	Consiglio Nazionale delle Ricerche (CNR)	276	5.06
2	Italy	823	15.08	2	Centre National de la Recherche Scientifique (CNRS)	178	3.26
3	England	672	12.32	3	University of London	121	2.22
4	Spain	383	7.02	4	National Gallery of Art	87	1.59
5	China	335	6.14	5	University of Florence	80	1.47
6	France	284	5.20	6	University of Pisa	78	1.43
7	Netherlands	199	3.65	7	University of California System	77	1.41
8	Germany	167	3.06	8	Metropolitan Museum of Art	67	1.23
9	Australia	159	2.91	9	University of Bologna	65	1.19
10	Belgium	152	2.79	10	Sorbonne University	63	1.15
Top 10 categories of articles				**Top 10 productive journals**			
Rank	**Research areas**	**Counts**	**Proportion (%)**	**Rank**	**Journal title**	**Counts**	**Proportion (%)**
1	Art	3437	62.98	1	*Journal of Cultural Heritage*	520	9.53
2	Chemistry	2129	38.01	2	*Studies in Conservation*	445	8.15
3	Spectroscopy	1642	30.09	3	*Heritage Science*	384	7.04
4	Archeology	1617	29.63	4	*The Burlington Magazine*	303	5.55
5	Materials science	1002	18.36	5	*Journal of Raman Spectroscopy*	293	5.37
6	Geology	885	16.22	6	*Art History*	276	5.06
7	Art humanities other topics	806	14.77	7	*Microchemical Journal*	264	4.84
8	Anthropology	308	5.64	8	*ARTnews*	209	3.83
9	Biochemistry Molecular Biology	157	2.88	9	*Artibus et Historiae*	196	3.59
10	Religion	156	2.86	10	*Art in America*	194	3.56
Top 10 productive authors							
Rank	**Author**	**Counts**					
1	Colombini, Marua Perla	54					
2	Madariaga, Juan Manuel	44					
3	Miliani, Costanza	41					
4	Edwards, Howell G. M.	41					
5	Vandenabeele, Peter	32					
6	Castro, Kepa	32					
7	Janssens, Koen	32					
8	Prati, Silvia	28					
9	Mazzeo, Rocco	27					
10	Brunetti, Brunetto G	24					

Source: Web of Science (Core Collection).

prominent position, with the National Gallery of Art among the world's top five contributors and the University of California System and the Metropolitan Museum of Art ranking close behind. Together, these institutions illustrate how national research councils, major universities, and world-renowned museums across Europe and North America underpin the global infrastructure of painting research.

The disciplinary landscape of painting research highlights its inherently multidisciplinary nature, encompassing material, technical, and cultural dimensions. Arts forms the core of the field, representing the single largest category with 3437 publications (62.98%) and anchoring the research in established traditions of art history and theory. The next most prominent contributions come from a cluster of scientific disciplines: Chemistry (38.01%), followed closely by Spectroscopy (30.09%), Archeology (29.63%), and Materials Science (18.36%), which collectively focus on the material attributes of artworks to inform authentication, analysis, and conservation. The scope is further diversified by also significant inputs from Geology (16.22%), as well as Anthropology (5.64%) and Religious (2.86%), which enrich the contextual understanding of painting within broader cultural and social frameworks.

This multidisciplinary composition is equally reflected in the field's publishing venues: they include both core venues in cultural heritage conservation and traditional art history, as well as broader interdisciplinary platforms. Technology-oriented journals such as *Journal of Cultural Heritage*, *Studies in Conservation*, *Heritage Science* and *Journal of Raman Spectroscopy* emphasize scientific approaches to painting conservation and restoration. These include the use of nanomaterials, spectroscopy, X-ray diffraction, and other advanced analytical techniques, which have advanced the scientific standardization of conservation practices and provided theoretical and practical support for the long-term preservation of painting cultural heritage. For instance, Cavaleri et al.[39] combined MA-XRF, multispectral imaging, FORS, FTIR, and Py-GC/MS to reconstruct the stratigraphy and conservation history of a sixteenth-century panel painting after Raphael in *the Journal of Cultural Heritage*[39]. In recent years, the research scope of such journals has expanded to encompass emerging topics such as

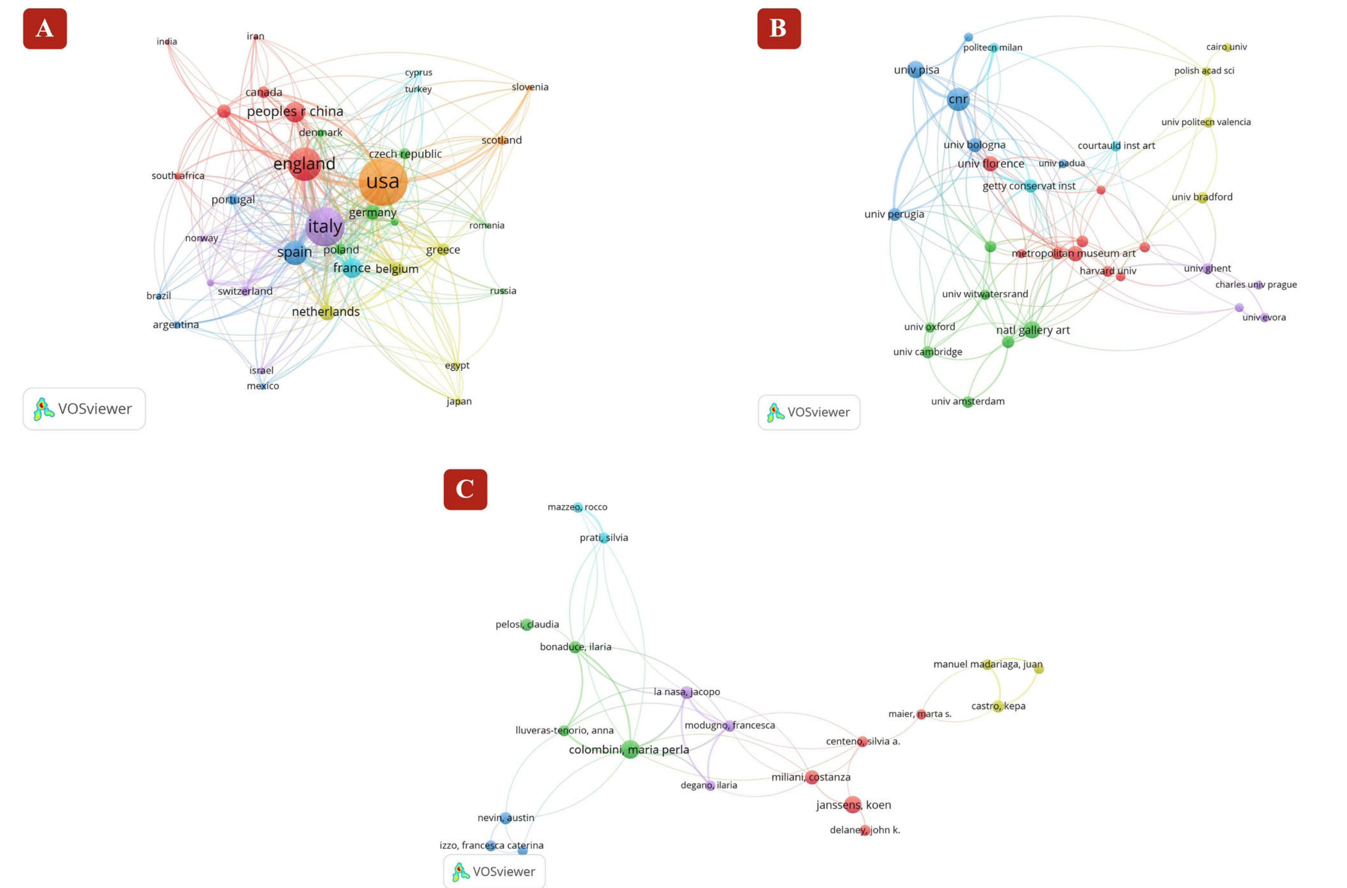

Fig. 3 | Global collaboration networks in painting art research at country, institutional, and author levels. **A** Country-level co-authorship network based on publications with ≥20 papers. **B** Institution-level co-publication network based on institutions with ≥26 papers. **C** Author-level co-authorship network including authors with ≥13 publications. In all panels, node size represents publication output, links indicate collaborative relationships, and colors denote clusters identified by VOSviewer. Source: Web of Science (Core Collection); visualized using VOSviewer.

digital image processing, 3D reconstruction, and AI-based image recognition. For example, Li et al.[40] published in *Heritage Science* a study that used text mining and perceptual assessment to reveal how clan-hall murals in Guangzhou encode family-based values[40]. In parallel, leading art history journals such as *The Burlington Magazine*, *Art History*, *Artibus et Historiae*, and *Art in America* continue to sustain disciplinary reflection from within the humanities. These journals often do not focus on technical or analytical investigation but rather foreground questions of artistic intention, formal language, and socio-historical meaning, encompassing both the"inward" study of form and style and the"outward"examination of context and interpretation. For example, Loh explored the tension between "repetition" and "originality" in seventeenth-century Italian Baroque painting in *The Art Bulletin*, thereby demonstrating the methodological depth of art-historical inquiry[41].

The same intellectual diversity is also evident in authorship patterns. According to our dataset, the most productive authors in painting research are primarily analytical chemists and conservation scientists who bridge material characterization with cultural-heritage interpretation. The most productive author is Maria Perla Colombini of the University of Pisa. Her research focuses on chromatographic and spectroscopic analyses of organic binders and degradation products in artworks. For instance, she (2003) developed a laser micro-sampling technique using an Er:YAG system to collect minute quantities of organic binders from painted layers without significant degradation, enabling precise FT-IR and GC-MS characterization[42]. Close behind are Juan Manuel Madariaga of the University of the Basque Country and Costanza Miliani of CNR-ISPC. Madariaga specializes in multi-analytical field methods, combining portable Raman and XRF spectroscopy to diagnose degradation phenomena in wall paintings and ceramics under real environmental conditions. For example, Madariaga et al. used portable Raman and XRF instruments to analyze sulfate and carbonate efflorescence in Pompeian murals, revealing how environmental exposure drives mineral alteration and deterioration[43]. By contrast, Miliani's work is distinguished by its focus on developing integrated, practical diagnostic workflows that primarily employ optical and vibrational spectroscopy conducted directly on the artwork surface. Her research effectively combines techniques such as reflection FT-IR, Raman spectroscopy, and XRF to address specific conservation challenges, including monitoring the cleaning of surfaces, diagnosing pigment degradation, and characterizing modern paint materials. Other prominent contributors, including Howell G. M. Edwards, Peter Vandenabeele, Kepa Castro, Koen Janssens, Silvia Prati, and Rocco Mazzeo, likewise emphasize cross-disciplinary methodologies grounded in conservation science, chemistry, and imaging.

Taken together, the preceding analysis outlines a field characterized by a distinct geographic core, a multifaceted intellectual structure, and a collaborative, cross-disciplinary authorship. Its center of gravity remains in Europe and North America, yet the field continues to expand through cross-continental collaboration. The analytical precision fostered by spectroscopy, chromatography, and data-driven methods complements the slower reasoning models in traditional art-historical research[44,45] generating more cumulative and diversified outcomes related to painting art, and making the interpretive process itself increasingly tangible, measurable, and collaborative. In this evolving landscape, painting research stands not as a divided domain between science and art, but as a shared terrain where method, matter, and meaning continually inform one another. The following section examines how these tendencies take shape within collaborative structures and thematic formations across the global research network.

Structural pattern

According to VOSviewer's clustering at the country level (≥20 papers) shown in Fig. 3A, global painting research presents a diversified and multipolar collaboration pattern. The red cluster, centered on England links Anglophone and Asia–Pacific countries such as Australia, Canada, China, and India. This reflects the structural influence of the English-language research ecosystem, including shared databases, publication venues, and funding channels that support transcontinental knowledge exchange. In the blue cluster, Spain, Portugal, Mexico, Brazil, and Argentina form an Iberian–Latin American network grounded in historical and linguistic ties, with research often focused on conservation and the material study of colonial and pre-Hispanic paintings. Centered on the Netherlands and Belgium, the gold cluster gravitates toward technical studies of pigments and imaging, often characterized by shared expertise in analytical and imaging methodologies. The purple cluster, anchored by Italy, is defined by its emphasis on conservation-oriented research, combining southern Europe's long tradition in heritage preservation with northern Europe's strengths in technical analysis. The cyan cluster, comprising France, Turkey, and Cyprus, forms a compact Franco-Mediterranean group centered on pigment and glaze studies linked to regional archeological resources. The orange cluster, led by the United States and connected to Scotland and Slovenia, highlights a science-oriented network active in diagnostic and imaging technologies. The green cluster, led by Germany and including Austria, Denmark, and Poland, represents a research community grounded in long-standing European academic networks and cultural heritage programs.

Figure 3B's institution-level co-publication network (≥26 papers) reveals six principal clusters, highlighting the close partnership between museums and universities in painting research. The red cluster brings together major university and museum partners across North America and Europe, including Harvard University, the Metropolitan Museum of Art, University College London, the University of Barcelona, and the Universities of Florence, London, Parma, and the Basque Country. Research in this cluster spans multiple dimensions, including the structural and environmental stability of painted supports, material characterization, and art-historical analysis. A representative study is the analysis of the *Mona Lisa* panel by researchers from the University of Florence and the Metropolitan Museum of Art, which identified contact areas and mechanical forces between the panel and its frame to evaluate stress distribution and microclimate performance[46]. The green cluster connects major museums and universities across Europe and Africa, including the British Museum, the National Gallery of Art, the University of Amsterdam, the University of Antwerp, the Universities of Cambridge and Oxford, and the University of the Witwatersrand. Its research focuses on imaging-based analysis, pigment alteration, and long-term material changes in paintings. For instance, a research team from the University of Amsterdam and the University of Antwerp (De Keyser et al.[47]) identified pararealgar and semi-amorphous pararealgar in Rembrandt's *The Night Watch*, revealing intentional pigment use and extending knowledge of seventeenth-century arsenic sulfide palettes[47]. The purple cluster, comprising Charles University, Ghent University, and the University of Évora, forms a European research network centered on methodological innovation in heritage science. The cluster shows a strong focus on developing portable and in situ Raman techniques for pigment analysis, as well as building reference spectral datasets that support material identification and conservation research. The gold cluster links Cairo University, the Polish Academy of Sciences, the Universitat Politècnica de València, and the University of Bradford, focusing on material characterization and the degradation of paintings and architectural surfaces. The blue cluster, formed by CNR together with the Universities of Bologna, Milan, Padua, Perugia, and Pisa, represents a concentrated Italian network dedicated to the technical study of paintings and architectural surfaces. Its research emphasis lies in reconstructing artists' materials and techniques, diagnosing degradation processes, and supporting conservation decision-making through integrated analytical investigation. A study on Caravaggio's *La Medusa* by teams from CNR and the University of Pisa exemplifies this focus, clarifying the painting's layer structure, pigment choices, and varnish history while revealing evidence of support reuse and past interventions[48]. The cyan cluster, linking the Courtauld Institute of Art, the Getty Conservation Institute, and Politecnico di Milano, centers on conservation science with a focus on paint materials, deterioration processes, and preventive strategies. The cluster's work emphasizes how environmental and mechanical factors affect paintings and how improved monitoring and treatment methods can support long-term preservation.

Turning to authors (Fig. 3C, ≥13 papers each), twenty high-output scholars organize into six thematic clusters. Leading figures in integrated spectral and imaging analysis appear in the red cluster, including Silvia A. Centeno of the Metropolitan Museum of Art, Costanza Miliani of CNR, John K. Delaney of the National Gallery of Art (Washington), Koen Janssens of the University of Antwerp, and Matthias Alfeld of Delft University of Technology. Working across institutions and continents, their research collectively demonstrates how reflectance imaging, XRF, and vibrational spectroscopy can be used in a complementary manner to investigate pigment chemistry and material change. For example, Ropret et al.[49], with Miliani and Centeno among the co-authors, refined Raman mapping methods for works of art, demonstrating how molecular imaging complements other spectroscopic data to reveal stratigraphic and compositional information beyond visual inspection[49]. The green cluster is primarily associated with the University of Pisa, where Maria Perla Colombini, Ilaria Bonaduce, Francesca Modugno, and Anna Lluveras-Tenorio, together with Claudia Pelosi from the University of Tuscia, have built one of the most influential teams in chromatographic and spectroscopic analysis of organic materials. Their work elucidates the chemical behavior of proteins, oils, and natural varnishes in aging and restoration contexts. For instance, Lluveras et al.[50], with Bonaduce and Andreotti among the co-authors, developed a GC-MS method to characterize glycerolipids, natural waxes, terpenoid resins, and proteinaceous materials in paint microsamples, demonstrating how chemical analysis can guide safe and effective restoration[50]. The blue cluster brings together Austin Nevin (Courtauld Institute of Art), Marcello Picollo (CNR-IFAC), and Francesca Caterina Izzo(Ca' Foscari University of Venice). This group focuses on diagnostic and preventive approaches in technical art history, developing portable and laser-based analytical systems for on-site monitoring and treatment of artworks. Their research integrates spectroscopy, multispectral imaging, and laser cleaning techniques to support condition assessment and conservation intervention, demonstrating how minimally invasive analysis can inform preservation while maintaining the integrity of cultural objects. The purple cluster comprises Ilaria Degano, Jacopo La Nasa, and Francesca Modugno from the University of Pisa. Their research centers on the chemical characterization and aging behavior of organic dyes, resins, and modern painting materials through chromatographic and mass spectrometric analyses. For example, La Nasa et al.[51] examined six decades of street art murals to identify pigments and binders, providing key data for developing conservation strategies for modern outdoor paintings and broadening the analytical basis for contemporary materials[51]. The core of the gold cluster lies at the University of the Basque Country and is represented by Kepa Castro, Maite Maguregui, and Juan Manuel Madariaga. Their work focuses on non-destructive spectroscopic characterization of pigments and mural materials, with particular attention to Raman and XRF applications in historic wall paintings. Through long-term methodological refinement, this team has significantly improved pigment identification and the study of degradation processes in colonial and early-modern artworks. The cyan cluster is anchored by Rocco Mazzeo and Silvia Prati from the University of Bologna, among others. Their research focuses on developing non-destructive and environmentally sustainable techniques for the cleaning and analysis of paintings and other heritage materials. For example, Ramacciotti et al.[52] introduced microporous electrospun nonwovens combined with green solvents to selectively

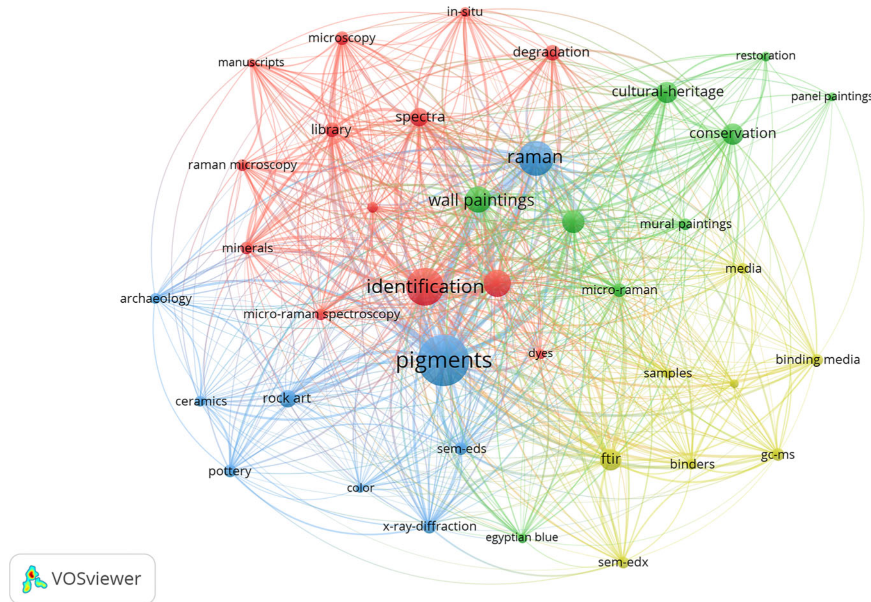

Fig. 4 | Keyword co-occurrence clustering map of painting art research topics. Source: Web of Science (Core Collection); visualized using VOSviewer.

Table 5 | Thematic clusters in painting art research based on keyword co-occurrence analysis

Cluster	Keywords
Red cluster	degradation; dyes; identification; in situ; library; manuscripts; micro-raman spectroscopy; microscopy; minerals; pigment identification; raman microscopy; spectra; spectroscopy
Yellow cluster	binders; binding media; ftir; gc-ms; mass-spectrometry; media; samples; sem-edx
Green cluster	conservation; cultural-heritage; egyptian blue; micro-raman; mural paintings; panel paintings; restoration; wall paintings; x-ray-fluorescence
Blue cluster	archeology; ceramics; color; pigments; pottery; raman; rock art; sem-eds; x-ray-diffraction

Generated from the present study using VOSviewer keyword co-occurrence analysis.

remove aged varnishes, demonstrating an effective and minimally invasive conservation approach[52].

Overall, mapping country, institutional, and author networks reveals painting research as anchored by established Western centers yet increasingly enriched by regional hubs in Asia, Latin America, and beyond. While traditional art historians have often worked alone[53], the advent of technical art history and digital humanities is driving a shift toward collaborative, lab-and-museum partnerships that bring together specialists in conservation science, analytical materials research, and art history. This emerging team-based model not only broadens methodological horizons and deepens analytical rigor but also correlates with a sustained rise in co-authored publications.

These collaborative dynamics are also reflected at the thematic level. Based on keyword co-occurrence analysis (≥45 occurrences), 39 terms formed four major clusters that reflect the growing intersection of material science, conservation studies, and archeological analysis in painting research (Fig. 4; Table 5).

The red and yellow clusters together represent the material science and technological dimensions of painting research, focusing on the material composition, chemical transformation, and analytical investigation of pigments and binders. Specifically, the red cluster focuses on the spectroscopic study and identification of pigments and minerals in paintings. The co-occurrence of terms such as "micro-Raman spectroscopy," "microscopy," "spectra," and "spectroscopy" highlights the use of analytical techniques. These techniques provide chemical and structural information from extremely small areas or microsamples, which helps reduce physical impact on fragile or culturally significant artworks. In conservation-oriented studies, such analyses often function as the first step in multi-phase diagnostic workflows[54]. The frequent appearance of keywords like "library" and "identification" reflects the role of spectral reference databases in pigment analysis and classification. For example, Fremout and Saverwyns developed a comprehensive digital Raman spectral library comprising nearly 300 synthetic organic pigments, which has been used in the study of contemporary paintings and has supported more accurate pigment identification, thereby facilitating informed conservation decisions[55].

In contrast, the yellow cluster is organized around the question of technique and organic composition. Its focus on "binding media," "binders," and "samples," analyzed through "FTIR" and "GC-MS," shifts the inquiry from what the pigment is to how it was suspended and applied. This approach advances the reconstruction of artists' working practices and provides a chemical basis for evaluating authenticity and degradation processes. Melo et al.[56], for instance, examined color degradation in medieval manuscript illuminations through a focus on organic media and material degradation, showing that binding media play a critical role in degradation processes as well as in shaping the perceptual impact of conservation treatments[56]. Another example is provided by Nodari and Ricciardi, who applied ER-FTIR spectroscopy to identify paint binders in illuminated manuscripts, demonstrating how gum Arabic and egg-based media can be distinguished even in complex pigment mixtures[57].

The green cluster centers on the applied objective of diagnosing deterioration and informing conservation strategies. The strong link between object types ("mural paintings," "panel paintings") and analytical techniques ("micro-Raman," "X-ray fluorescence") within the context of "cultural heritage" defines a paradigm where science is in the service of conservation. For example, Philippova et al.[58] investigated twelfth-century wall paintings from the Christ's Transfiguration Cathedral in Pskov (Russia), combining complementary physico-chemical analyses to identify

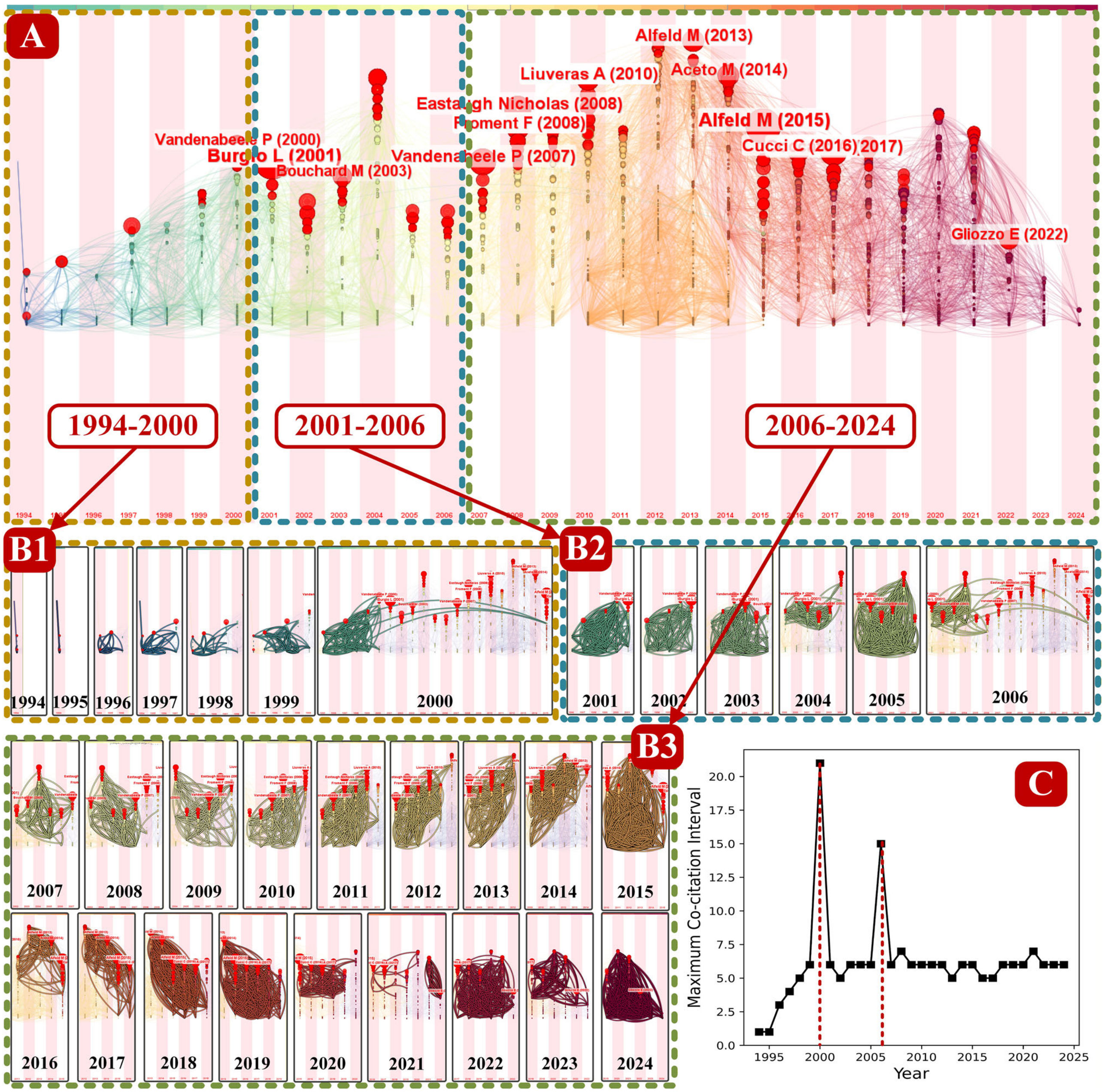

Fig. 5 | Annual knowledge flow patterns in painting art research. A Overall citation-based knowledge flow in painting art research from 1994 to 2024. **B** Time-sliced visualization of the citation flow based on the maximum co-citation interval, which is divided into three phases: (B1) growth phase (1994–2000), (B2) relatively stable phase (2001–2006), and (B3) extended stable phase (2007–2024). **C** Distribution of the maximum co-citation interval for painting art research. Source: Web of Science (Core Collection); visualized using CiteSpace.

pigments and diagnose salt efflorescence, directly informing conservation interventions[58].

Finally, the blue cluster asks the broadest study question: what is the cultural and temporal significance? It connects painting materials (“pigments,” “color”) to archeological contexts (“ceramics,” “pottery,” “rock art”). Techniques such as “SEM-EDS,” “X-ray diffraction” and “Raman” indicate an emphasis on elemental and structural characterization of archeological paints. For example, Gheco et al.[59] analyzed rock paintings from the Oyola Caves in Argentina using a micro-stratigraphic and multi-analytical approach, revealing variations in pigment composition and application techniques that reflected distinct phases of artistic production. This study exemplifies how archaeometric research can reconstruct technological practices and temporal complexity within painting traditions[59].

Viewed as a whole, the keyword network reveals a methodological maturation within painting research, particularly in the field of technical art history. Analytical focus has shifted from isolated material identification toward the investigation of material behavior, interaction, and long-term transformation. This transition reflects a growing tendency to integrate physical, chemical, and environmental data into interpretive models of artistic process and conservation strategy. As Fowler observes, paintings are now understood as “dynamic objects that exist beyond the surface, containing material worlds invisible to the naked eye”[60]. In this sense, the field increasingly conceives of paintings not merely as composite material entities but as evolving systems whose stability, alteration, and restoration form part of their analytical and historical understanding.

This thematic consolidation is mirrored by the long-term structure of the citation network. Between 1994 and 2024, the citation network of

Table 6 | Top influential articles based on citation (burstness) and degree centrality

Rank	Citation frequency (Burstness)	Representative influential articles		Degree centrality	Representative influential articles	
1	29 (15.82)	Burgio et al.[66]	Library of FT-Raman spectra of pigments, minerals, pigment media and varnishes, and supplement to existing library of Raman spectra of pigments with visible excitation	58	Bahn[97]	Prehistoric rock art: polemics and progress; the 2006 Rhind Lectures for the Society of Antiquaries of Scotland
2	29 (15.18)	Alfeld et al.[67]	Strategies for processing mega-pixel X-ray fluorescence hyperspectral data: a case study on a version of Caravaggio's painting Supper at Emmaus Check for updates	58	Blanc et al.[73]	Trance and shamanic cure on the South American continent: Psychopharmacological and neurobiological interpretations
3	22 (12.32)	Vandenabeele et al.[68]	A decade of Raman spectroscopy in art and archeology	58	Stewart et al.[98]	Enaction : toward a new paradigm for cognitive science
4	22 (10.97)	Eastaugh et al.[64]	Pigment Compendium: A Dictionary and Optical Microscopy of Historic Pigments	58	Akers et al.[74]	A prehistoric mural in Spain depicting neurotropic psilocybe mushrooms?
5	22 (10.89)	Coccato et al.[69]	On the stability of mediaeval inorganic pigments: A literature review of the effect of climate, material selection, biological activity, analysis and conservation treatments	58	Beaumont[99]	The Edge: More on Fire-Making by about 1.7 Million Years Ago at Wonderwerk Cave in South Africa
6	18 (10.41)	Froment et al.[72]	Raman identification of natural red to yellow pigments: Ochre and iron-containing ores	58	Boes et al.[100]	Behavioral effects of congenital ventromedial prefrontal cortex malformation
7	18 (9.96)	Aceto et al.[70]	Characterization of colorants on illuminated manuscripts by portable fiber optic UV-visible-NIR reflectance spectrophotometry	58	Bednarik et al.[101]	An etiology of hominin behavior
8	18 (9.47)	Alfeld et al.[102]	A mobile instrument for in situ scanning macro-XRF investigation of historical paintings	58	Bednarik et al.[103]	The Nexus between Neurodegeneration and Advanced Cognitive Abilities
9	18 (9.14)	Cucci et al.[71]	Reflectance hyperspectral imaging for investigation of works of art: Old master paintings and illuminated manuscripts	58	Butler et al.[104]	Evolutionary constraints on visual cortex architecture from the dynamics of hallucinations
10	18 (8.6)	Lluveras et al.[50]	GC/MS analytical procedure for the characterization of glycerolipids, natural waxes, terpenoid resins, proteinaceous and polysaccharide materials in the same paint microsample avoiding interferences from inorganic media	58	Carhart-Harris et al.[105]	Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin

Source: Web of Science (Core Collection); analysis conducted in CiteSpace.

painting research exhibits a clear temporal structure, which can be divided into three phases based on the trend of the maximum co-citation interval (Fig. 5A, C): a growth phase from 1994 to 2000 (Fig. 5B1), a relatively stable phase from 2001 to 2006 and 2007 to 2024 (Fig. 5B2, B3), and two pronounced peaks around 2000 and 2006 that represent exceptional long-range co-citations within the network. These peaks indicate moments when earlier studies retained an unusually long influence across the field.

During the first phase (1994–2000), the maximum co-citation interval increased steadily, indicating that early studies were repeatedly paired with much later publications and therefore maintained a long presence within the citation structure. The pronounced peak around 2000 shows that several early technical studies continued to be co-cited across an unusually extended span. For example, Chiavari et al.[61] which introduced analytical pyrolysis for pigment and binder characterization, and Heimberg[62], which examined varnish layers in works of art, frequently form long-distance co-citation pairs with later syntheses such as Pollard and Heron's *Archeological Chemistry*[63]. This combination reflects complementary contributions in material characterization, varnish analysis, and subsequent methodological consolidation. The pattern suggests that early empirical studies offered distinct yet mutually reinforcing perspectives that were later integrated into broader methodological overviews in painting research.

From 2001 to 2024, the network enters a relatively stable configuration, with the maximum co-citation interval fluctuating around six years, reflecting a regular cycle in which new research directions or methodological updates emerge and consolidate within painting research. The second pronounced peak around 2006 again marks a moment when earlier publications maintained long-range co-citation ties with later works, a structure visible in combinations involving Eastaugh et al.'s *Pigment Compendium*[64] and Pollard and Heron[65]. As Leydesdorff et al.[65] note, "short-term citations can be considered as currency at the research front, whereas long-term citations contribute to the codification of knowledge claims into concept symbols" [66]. In this context, these peaks signal periods when particular bodies of work became consolidated as durable points of reference within the field's evolving research trajectory.

Bibliometric indicators of citation frequency and burstness (Table 6) highlight how painting research has consolidated around a cluster of material- and technology-oriented studies, shaping the field's evolving methodological landscape. Collectively, these works show sustained efforts to standardize analytical procedures, build shared data resources, and ensure reproducible experimental outcomes.

The top three most influential publications by Burgio et al.[66], Alfeld et al.[67], and Vandenabeele et al.[68] represent successive milestones in this consolidation. Burgio's FT-Raman spectral library established one of the earliest multi-wavelength pigment databases, encompassing 60 pigments and media, and remains widely referenced in heritage science and digital spectral databases[66]. Alfeld and Janssens's 2015 study advanced data-processing strategies for macro X-ray fluorescence (MA-XRF) imaging, exemplified through the analysis of Caravaggio's *Supper at Emmaus*[67]. Vandenabeele et al.'s 2007 review of Raman spectroscopy in art and archeology synthesized a decade of innovation in excitation techniques, instrumentation, and field applications, formalizing a coherent technical canon that continues to shape pigment research today[68].

Beyond these core methodological pillars, other high-impact studies have extended painting research along three converging lines of development. First, pigment science matured through integrative reference works such as Eastaugh et al.'s *Pigment Compendium* and Coccato et al.'s[69] review of medieval pigment stability, both of which linked optical, chemical, and environmental data to practical conservation. Second, analytical chemistry

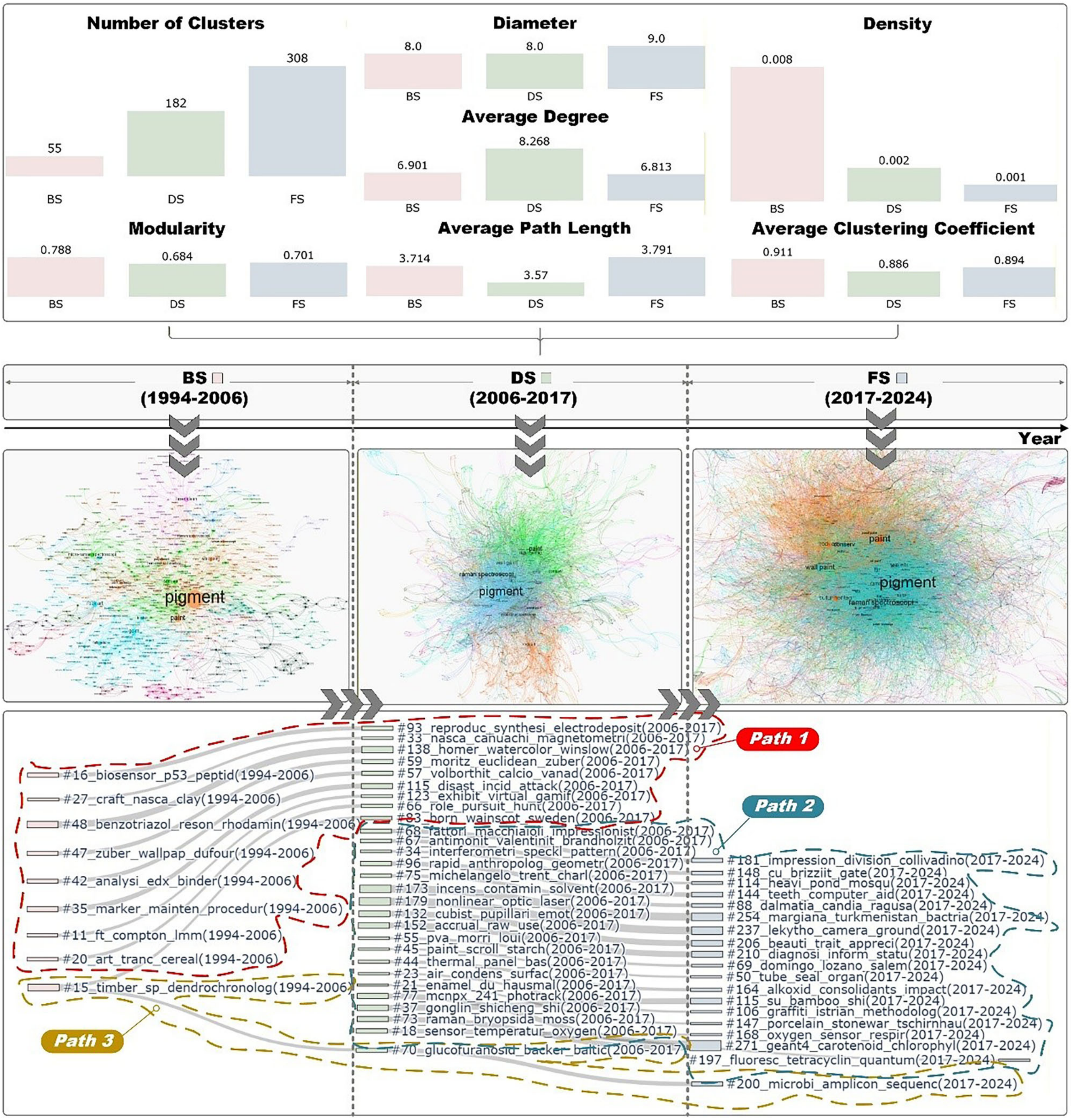

Fig. 6 | Structural and thematic evolution of painting art research across three stages. Source: Web of Science (Core Collection); visualized using CiteSpace.

diversified through innovations in reflectance spectroscopy (Aceto et al.[70]; Cucci et al.[71]) and GC-MS protocols (Lluveras et al.[50]), allowing more precise analysis of multiple material types from very small samples. Third, provenance-oriented and mineralogical research, exemplified by Froment et al.[72], expanded knowledge of pigment formation and geographic distribution, extending the scope of laboratory findings into historical and material contexts[72].

Publications with high degree centrality serve as connective nodes that bridge empirical technique with conceptual analysis. Works such as Paul G. Bahn's *Prehistoric Rock Art: Polemics and Progress* (2010) study of the Selva Pascuala mural illustrate this linkage. Drawing on the 2006 Rhind Lectures, Bahn synthesized global discoveries on prehistoric painting, reassessing interpretive paradigms such as the"shamanic"model while integrating imaging and conservation perspectives[73]. Akers extended this dialogue by linking iconography, ethnography, and mycology, arguing that the mural's fungoid figures may depict Psilocybe mushrooms associated with ritual practice[74]. Drawing on archeological and ethnographic perspectives, these studies applied technical evidence within broader historical and cultural frameworks, illustrating how empirical findings enrich interpretations of meaning, ritual, and artistic practice.

In sum, the citation evidence suggests that the field's methodological core has become both stable and generative, with a small number of enduring analytical approaches supporting continuous, incremental advances across painting research.

Temporal evolution

According to Fig. 6, a visual analysis of the painting research knowledge network from 1994 to 2024 reveals a three-phase chronological evolution, which reflects a gradual transition from technique-oriented exploration to systematic, interdisciplinary research, accompanied by increasingly globalized knowledge linkages. More detailed information is provided in Supplementary Table S1.

In the Blooming Stage (1994–2006), scientific identification, provenance analysis, and early imaging and spectroscopic techniques already formed the empirical backbone of painting research, while interdisciplinary integration and interpretive synthesis were still in early development. During this period, the citation network exhibited a relatively well-defined modular structure, with 55 clusters and a modularity of 0.788, indicating clear thematic differentiation. The network remained highly cohesive, as indicated by an average clustering coefficient of 0.911. The average degree (6.901) and average path length (3.714) suggest that researchers were closely connected through shared analytical methods and technical concerns. This high connectivity existed despite the low density (0.008), which is typical of emerging interdisciplinary fields. Cluster #42_analysi_edx_binder centers on binder identification and micro-scale material analysis, featuring recurrent terms such as paint binder, SEM-EDX analysis, XRD analysis, and GC-MS analysis (each at 0.0049) that point to the establishment of physicochemical characterization as a foundational investigative tool. Cluster #15_timber_sp_dendrochronolog reflects an early emphasis on provenance and material sourcing, where keywords like provenance (0.0097), dendrochronology (0.0049), and ornament stone (0.0049) signal the growing use of wood-ring dating and geological identification to reconstruct object histories.

During the Development Stage (2006–2016), technical analysis was increasingly combined with questions about how paintings behave in changing physical and digital environments. Correspondingly, clusters expand to 182, modularity decreases to 0.684, the average clustering coefficient remains high at 0.886, average degree rises to 8.268, the average path length shortens to 3.57, and density further declines to 0.002. The drop in modularity together with higher average degree indicates more active citation exchange across clusters and methodological convergence. Cluster #34_interferometri_speckl_pattern highlights this trend, gathering studies on environmental and structural monitoring. Terms such as relative humidity (0.0026), condition survey (0.0023), and speckle interferometry (0.0011) reveal a shift toward examining paintings as dynamic material systems responsive to climate and stress. Cluster #96_rapid_anthropolog_geometr captures another emerging direction: the adoption of 3D modeling and virtual reconstruction for surface documentation. Keywords like 3D virtual model, rapid prototyping, and geometric morphometrics (all at 0.0011) reflect an expanding toolkit for digital visualization and comparative morphology.

In the Flourishing Stage (2016–2024), the field expands into a more differentiated landscape, where established research traditions coexist with newly emerging methodological directions. The network grows to 308 clusters, with a modularity of 0.701, an average clustering coefficient of 0.894, an average degree of 6.813, and an average path length of 3.791, while density decreases to 0.001. This combination of lower density but sustained clustering indicates a much larger and more differentiated field in which well-formed communities remain active but increasingly connected across regions and subfields. Cluster #69_domingo_lozano_salem exemplifies the surge in transregional and trade-related material research. Recurring terms such as China trade, Manila, and pith paint (each at 0.0015) point to renewed attention to circulation networks, workshop exchanges, and global material flows. Cluster #115_su_bamboo_shi reflects sustained scholarship on East Asian literati painting, illustrated by terms like Su Shi, Mi Fu, and literati paint (each at 0.0012), underscoring the continued relevance of textual, stylistic, and material research traditions within Chinese art history. Other clusters document significant methodological diversification. #210_diagnosi_inform_statu incorporates digital image analysis and conservation status (0.0007 each), showing how computational diagnostics now support monitoring and treatment. Meanwhile #200_microbi_amplicon_sequenc, with terms such as bacterial community and amplicon sequencing (0.0007 each), signals the rise of microbiological approaches to deterioration and biodeterioration assessment.

Throughout this evolution, three knowledge-migration trajectories stand out. The first knowledge transfer path (i.e. Path 1 in Fig. 6) llustrates how analytical methods originating from materials science and technical archeology gradually reshaped painting research from the late 1990s to the mid-2010s, driving a methodological shift toward contextually informed material interpretation. Early studies concentrated on refining spectroscopic and microscopic techniques for examining complex pigment and binder systems. McCabe et al. [75]., for instance, enhanced the adhesion of rhodamine dyes to silver colloids to improve the sensitivity of surface-enhanced resonance Raman scattering (SERRS), providing a more stable platform for micro-area pigment identification and encouraging the broader adaptation of SERS-based protocols in heritage analysis[75].

From the mid-2000s onward, analytical innovation extended beyond laboratory refinement toward field applicability and environmental monitoring. García-Diego and Zarzo (2010) exemplified this shift by applying microclimate diagnostics to the frescoes of Valencia Cathedral, using principal component analysis to interpret humidity fluctuations and guide preventive conservation[76]. Besides, Doherty et al.[77] developed SERS-active methylcellulose gels optimized for portable Raman analysis, allowing in situ spectral measurement with minimal penetration and surface disturbance[77]. Together, these studies reflect a growing emphasis on on-site analytical adaptability, combining laboratory precision with contextual awareness and minimal intervention.

Meanwhile, across roughly two decades of development, the research focus further expanded from the characterization of materials to the reconstruction of pigment provenance and technological exchange. Castro et al.[78] used Raman microprobe spectroscopy to reconstruct the pigment palette of *Les Monuments de Paris* wallpaper (1812), revealing the early diffusion of synthetic colorants in nineteenth-century Europe[78].Building on such provenance-oriented inquiries, Brichzin and Herm (2012) analyzed *Les Vues du Brésil* (1829), discovering synthetic ultramarine layered on mulberry paper imported from East Asia, providing evidence of global material circulation within European decorative art[79]. This progression from micro-analytical refinement to transregional material contextualization exemplifies how scientific methods evolved into interpretive tools, linking laboratory evidence with broader cultural and historical perspectives in painting research.

The second research path (i.e., Path 2 in Fig. 6) captures a distinct evolution in painting research from 2006 to 2024, marked by a progression from materials and structural analysis carried out in conjunction with contextual interpretation toward intelligent modeling and broader interpretive approaches.

During the 2006–2016 period, research emphasis lay in refining structural and optical diagnostics to clarify interactions among pigments, binders, and substrates. Rampazzi et al. [80], for instance, combined optical microscopy, SEM, and infrared spectroscopy to examine pigment-substrate relationships in Baroque plaster, establishing a microstructural foundation for analyzing decorative techniques[80]. Similarly, Čechák et al. [81] investigated the Křivoklát Altarpiece using micro-XRF, EDS mapping, and electron microscopy to reconstruct a rare Late Gothic gilding method involving bismuth powder beneath gold and silver leaf[81]. This interdisciplinary study revealed previously unrecognized material innovations and workshop practices, underscoring the capacity of microscopic and spectral analyses to reconstruct artistic techniques.

From 2016 onward, digital imaging and computational modeling became increasingly important tools. Multispectral imaging, RTI, and 3D microscopy supplied high-resolution documentation needed for both physical analysis and virtual reconstruction, while machine-learning and networked models enabled automated condition assessment and large-scale pattern extraction. For instance, Gaiani et al. [82] used digital reconstruction to reanalyze proportional systems[82], and Yuan et al. [83] applied an improved Res-UNet to detect craquelure and paint loss in palace murals[83], illustrating the potential of data-driven methods to extend monitoring and analysis from individual objects to large-scale collections. This convergence reflects parallel advances in imaging hardware, computational methods, and conservation practice.

Meanwhile, sustained art-historical inquiry deepened the understanding of East Asian painting traditions. For example, Xue reexamined the *Illustration to the Second Ode on the Red Cliff*, revealing how Li Gonglin's style was repurposed for imperial commemoration[84], while Sturman reconstructed the authenticity and context of Su Shi's *Old Tree, Rock, and Bamboo*[85]. These studies demonstrate the vitality of context-oriented analysis in Chinese art history, situating painting interpretation within broader social, cultural, and historical contexts.

Path 3 (i.e., Path 3 in Fig. 6) traces a coherent shift in painting research from macroscopic provenance studies toward microscopic and molecular-level investigation of organic materials and their degradation. In the late 20th and early 21st centuries, as represented by cluster #15 (timber_sp_-dendrochronolog), dendrochronology emerged as a pivotal method for tracing the origin and circulation of timbers used in artworks, thereby illuminating the material flows and historical contexts embedded within these objects. Foundational research, such as the study by Haneca et al.[86] on Baltic timbers, documented the large-scale import of wood and its use in art production, reframing artworks as quantifiable historical evidence[86]. As indicated in Fig. 6, this research tradition, embodied by cluster #15 (timber_sp_dendrochronolog), not only continued within Path 3 but also contributed to a parallel stream in Path 1 focused on environmental and regional timber analysis.

From around 2006 to 2017, as indicated by cluster #70 (glucofuranosid_backer_baltic), the focus of technical studies shifted toward the identification of organic and inorganic components such as pigments, dyes, and resins. This period marks a methodological transition from provenance tracing to the reconstruction of artistic techniques and pigment lineages. Casanova-González et al.[87], for example, applied SERS to characterize traditional Mexican dyes including cochineal, brazilwood, and calendula, providing essential reference spectra for non-destructive pigment identification[87]. Meanwhile, microscopic spectroscopy and Raman imaging were increasingly used to analyze wallpapers and paper-based artifacts, identifying pigments such as Prussian blue, Scheele's green, and vermilion, as well as binding media composed of vegetable gums and proteins.

Recent studies have further advanced toward microbial and molecular analysis. Saridaki et al. [88] employed high-throughput 16S rRNA sequencing to examine bacterial communities on wood, marble, and fresco surfaces, revealing distinct microbial compositions across materials[88]. Building upon earlier material identification research, such work increasingly explores how biological and environmental processes affect the long-term transformation of artworks, expanding the analytical scope from chemical to ecological dimensions.

Overall, the synthesis of the three trajectories highlights a shift in how painting is approached as an object of knowledge. Recent studies no longer treat pigments, binders, and supports as isolated material facts, but examine how their behaviors unfold under changing environmental, chemical, and temporal conditions. At the same time, analytical practice has broadened from single-technique diagnosis to the coordinated use of methods drawn from physics, chemistry, biology, and environmental science, producing evidence that is both finer in scale and wider in interpretive reach. Rather than framing scientific data and historical inquiry as separate domains, current research increasingly uses material findings to open questions about circulation, practice, and artistic intention. In this sense, the convergence of the three paths points not simply to technical advancement, but to an expanding analytical imagination that links process, context, and meaning within a more integrated understanding of painting.

Discussion

Over the past thirty years, painting research has transformed from a narrowly defined art-historical discipline into a dynamic, globally interconnected field where traditional art-historical approaches are increasingly complemented by conservation science, digital technologies, and interdisciplinary collaboration. To systematically capture this evolution, this study designed a new bibliometric-based "PDU" framework, which allows for a multi-layered investigation across distributional trends, structural relationships, and temporal development. The innovation of the PDU framework lies in its integration of the strengths of traditional bibliometric methods like publication counts, co-citation analysis, and co-word clustering, while extending them in a systematic, multi-dimensional, and operationalizable manner. Moreover, this approach is not only applicable to painting research but can also be extended to other humanities disciplines or interdisciplinary fields, providing a novel tool for comprehensively understanding knowledge structures and developmental trends within a field.

The distributional analysis shows sustained growth in global output, with the United States, Italy, and England remaining central while China and Spain increasingly contribute to the field's internationalization. Structurally, museums and universities form the core research nodes, driving collaborations that bring together art historians, conservators, analytical scientists, and digital specialists. The topic analysis further identifies a stable methodological cluster centered on pigment identification, binding-media analysis, conservation diagnostics, and archeological materials, reflecting both consolidation and diversification of technical approaches. The temporal and knowledge-flow analyses reveal a gradual evolution from early, exploratory technical tests to the formation of systematic analytical frameworks and, more recently, to diversified, multi-path developments that link spectroscopy, imaging, provenance studies, and digital modeling. These findings contribute to a more comprehensive understanding of the development of painting research. By moving beyond research approaches limited to a single art-historical or other disciplinary perspective, and beyond predominantly qualitative analytical modes, the results provide a broader analytical space for reflection, offering potential value for scholars engaged in various aspects of painting studies.

Despite advances in technical and digital art history, particularly in material analysis, digital modeling, and visual presentation, much research still focuses on localized technical applications and dataset-driven analysis, with limited attention to broader cultural contexts or theoretical frameworks[9]. Such work often privileges empirical accuracy and visual replication while underemphasizing interpretive and stylistic questions central to art-historical inquiry; in some cases, an overreliance on analytical techniques without sufficient contextual grounding can produce partial or misleading readings[54]. Text-mining evidence further suggests this gap: Näslund et al. [89] show that although many studies cite canonical art-historical theories, few engage deeply with major recent theoretical developments such as feminist or postcolonial critique, leaving technical studies at the level of surface data comparison and with limited reflection on issues like canon formation or epistemic bias[89]. At the same time, traditional art-historical research may neglect the material and technical dimensions of artworks, while the material perspectives offered by conservators and conservation scientists remain, at least to some extent, peripheral within the discipline[90]. As Carlyle observed, for the art historian to ignore the material aspects of paintings is to leave out something of vital importance to the artist[91]. This mutual disconnect has long hindered deeper methodological integration, suggesting that a genuinely synthetic tendency for painting research must bridge the interpretive insights of art history with the evidential precision of material and conservation science.

The emergence of these challenges is closely related to existing systems of academic evaluation and the organization of interdisciplinary collaboration. On the one hand, traditional art historians used to regard technology as a supportive analytical aid rather than a fully integrative research dimension. Given the humanities' emphasis on textual publication as the primary form of scholarly output, their engagement in technical collaborations is sometimes constrained in both enthusiasm and methodological depth[44]. On the other hand, projects led by technical specialists, though capable of generating large volumes of empirical data, may focus predominantly on specific analytical problems or dataset construction, sometimes at the expense of historical interpretation or esthetic sensitivity. These asymmetries sometimes create hierarchical structures in which art historians participate more as consultants than equal partners[92], thereby constraining the depth of methodological integration and the potential for genuine theoretical exchange. Moving forward, painting research needs to overcome this instrumental mode of cooperation by integrating technological tools with clearly articulated art-historical questions and by expanding evaluation systems to better recognize interdisciplinary scholarship. Attention should also be given to structural imbalances, including Western-centrism in data selection and model building. Strengthening cross-regional resource sharing and developing more inclusive data infrastructures will help foster a more balanced and genuinely global framework for knowledge co-construction.

This study also has several limitations. First, although the WoS database offers broad coverage and provides a comprehensive and actionable dataset to support the analysis of painting research, including publications indexed in the Art & Humanities Citation Index, its overall indexing criteria tend to favor English-language journals and empirical research in fields such as the natural and life sciences[93]. As part of the humanities, traditional painting studies may publish key findings in sources not covered by WoS[94–96] including journals, books, and other informal publications. Similarly, in art conservation science and technical art history, some important contributions appear in specialized bulletins or institutional publications that are not indexed by major citation databases, such as the National Gallery London Technical Bulletin, which is widely read by researchers in the field of technical art history. In addition, while topic keywords such as "paint*" and "pictorial art" help retrieve relevant literature, they cannot fully capture the diversity of painting-related scholarship[44], especially interpretive research focusing on specific artists or movements, which may lack generalizable terms. Nevertheless, following expert evaluation and careful screening of our dataset, the results of this study are not expected to be significantly biased and can still provide a relatively comprehensive and reliable reference for painting research. Future studies could further address these issues by incorporating multilingual and non-journal sources and adopting mixed-method approaches to provide deeper contextual insights.

Data availability

The bibliometric data supporting the findings of this study were obtained from the Web of Science Core Collection (1994–2024). These data are available from Clarivate Analytics, subject to subscription or institutional access, and were analyzed using standard bibliometric methods.

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Author contributions

J.L. conducted the primary data analysis. C.Y. designed the methods section and created the visualizations using CiteSpace and Plotly. All authors contributed to manuscript editing and revision, and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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