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A Human–AI Compass for Sustainable Art Museums: Navigating Opportunities and Challenges in Operations, Collections Management, and Visitor Engagement

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Abstract

This paper charts AI's transformative path toward advancing sustainability within art museums, introducing a Human–AI compass as a conceptual framework for navigating its integration. It advocates for human-centric AI that optimizes operations, modernizes collection management, and deepens visitor engagement—anchored in meaningful human–technology synergy and thoughtful human oversight. Drawing on extensive literature review and real-world museum case studies, the paper explores AI's multifaceted impact across three domains. Firstly, it examines how AI improves operations, from audience forecasting and resource optimization to refining marketing, supporting conservation, and reshaping curatorial practices. Secondly, it investigates AI's influence on digital collection management, highlighting its ability to improve organization, searchability, analysis, and interpretation through automated metadata and advanced pattern recognition. Thirdly, the study analyzes how AI elevates the visitor experience via chatbots, audio guides, and interactive applications, leveraging personalization, recommendation systems, and co-creation opportunities. Crucially, this exploration acknowledges AI's complex challenges—technical-operational, ethical-governance, socioeconomic-cultural, and environmental—underscoring the indispensable role of human judgment in steering its implementation. The Human-AI compass offers a balanced, strategic approach for aligning innovation with human values, ethical principles, museum mission, and sustainability. The study provides valuable insights for researchers, practitioners and policymakers, enriching the broader discourse on AI's growing role in the art and cultural sector.

Keywords: Artificial Intelligence; sustainability; art museums; Human–AI collaboration; AI integration challenges; AI ethics

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1. Introduction

Artificial Intelligence (AI) has rapidly expanded in the 21st century, with bibliometric analyses indicating a research surge from the 1990s to 2019 [1,2]. More specifically, publications and articles on AI applications in museums have significantly increased since 2010, particularly from China, Italy, and the United States, with a sharp rise in output from 2019, peaking in 2023 [3].

The evolving symbiotic synergy between humans and AI is catalyzing the transformation of critical sectors, driving efficiency, innovation, and competitiveness, while unlocking new opportunities for sustainable growth and societal progress [4].

Over the past decade, AI has been recognized as "critical to operational efficiency" and "a customer service imperative" prompting substantial investments from emerging tech companies [5]. AI's impact on economic development—manifested through improved decision-making, accelerated innovation and more effective social governance— alongside increasing global research on its economic applications underscore AI's growing role in shaping the future economy [6].

This trend is further supported by bibliometric analyses of AI publications backing the Sustainable Development Goals (SDGs)—particularly SDG 11, which aims to enhance urban environments and cultural aspects. This highlights AI's transformative potential in advancing sustainability, and driving overall development [7].

In cultural institutions, while AI-driven personalization significantly enhances visitor engagement, satisfaction, and brand perception [8], AI remains primarily an enabling tool and not a main driver for increased attendance with its adoption heavily reliant on a country's digitization policies and funding [9].

AI's self-learning and self-improving abilities make it well-suited for museum environments, where continuous performance improvement and responsiveness to user needs are essential [10]. As such, AI plays an increasingly vital role in helping museum better understand their audiences and improve overall management across functions ranging from trend analysis and targeted marketing to edutainment, exhibit modernization, and audiences' engagement, especially among younger generations like Gen Z [10–15].

On the other hand, AI systems still face significant limitations, including mechanical AI's inability to grasp context, thinking AI's inherent opacity and biases, and feeling AI's lack of true emotional understanding [16]. Despite its innovative potential and transformative applications across cultural sector that contribute to economic and broader sustainability goals, multifaceted challenges hinder AI's widespread implementation, underscoring the necessity of safeguarding cultural sensitivity, fostering interdisciplinary collaboration and developing robust ethical guidelines adapted to museum contexts [14,15,17,18].

The tension between AI innovation and responsible application is particularly pronounced in art museums, where AI is redefining how art is exhibited, experienced, interpreted, curated, preserved, and even created [17,19,20]. A prime example is Dataland, an AI-centered digital creativity museum opening in Los Angeles in 2025, aiming to merge artistic expression with ethical data use and a sustainable future [21].

Responding to growing academic interest in AI's role within museums, this article addresses the fragmented understanding of how its diverse applications can advance sustainability goals, critically engaging with inherent ethical, institutional, and human-centered implementation challenges. Focusing on three key areas—operational efficiency, collection management, and visitor experience—it offers an integrated perspective on AI's potential and limitations, arguing that, while innovative, it is not a universal solution and must be strategically and meaningfully embedded within the values and specific needs of each cultural institution. Its core contribution lies in outlining a framework for the responsible and sustainable AI adoption in the museum sector.

2. From AI Definition to Museum Practice: A Brief Overview

Artificial Intelligence refers to the capacity of computational systems to exhibit or replicate "intelligent behavior" [22], encompassing human-like abilities such as reasoning, performing physical tasks, and engaging in emotional interaction [16], or, as Sheikh et al. define, complex human skills like perception, cognition, and decision-making [23].

In a more precise definition, the European Commission's High-Level Expert Group on Artificial Intelligence (AI HLEG) describes AI as "systems that display intelligent behavior by analyzing their environment and taking actions –with some degree of autonomy– to

achieve specific goals" [24]. However, while AI excels at structured tasks and struggles with human-like abilities, as per Moravec's paradox, ongoing technological advancements constantly redefine its boundaries and definitions, turning past breakthroughs into commonplace achievements [23,25].

Since the mid-20th century, AI has evolved through waves of enthusiasm and retreat [23], now advancing to multiagent systems capable of tackling complex tasks [20]. Machine learning (ML), a key data analysis method, empowers systems to learn from large datasets without explicit programming [26,27] primarily via unsupervised and supervised learning [2]. In museums, AI utilizes descriptive and predictive analytics, leveraging ML techniques to interpret data and provide contextual insights [12].

Similarly, Generative AI (GenAI), which has surged since 2021, is increasingly enabling new forms of creative expression and visual storytelling within museum settings [28]. GenAI automates the creation of high-quality digital content (text, images, music) by leveraging advanced AI systems and large-scale models that interpret human intent, enabling fast and efficient generation [29]. By 2025, its use has expanded beyond technical tasks to include emotional support, personal organization, self-discovery and growth, sparking both excitement and concern over its impact on human cognition, privacy, and societal dynamics [30].

Overall, in the museum context, working in concert with human creativity and emotional nuance, modern AI integrates mechanical, analytical, affective and creative intelligence. It automates tasks using techniques such as classification, clustering, and content generation, recognizes patterns and supports decision-making through ML, neural networks, and deep learning (DL), while simultaneously interacting with humans via intelligent voice recognition, Natural Language Processing (NLP), sentiment analysis, chatbots, virtual agents, and multimodal interfaces [10,11,16,31].

3. Methods

To investigate the dynamics of human–AI synergy on museum operations, collection management, and visitor experience, along with the associated challenges it entails, we employed the method of an extended literature review, complemented by secondary data classification, analysis, and interpretation techniques. The methodological design was structured around the following research questions, which guided the scope, source selection, and analytical focus of the study:

1. In what ways can AI improve art museum operations (e.g., management, strategy, visitor services, core technical processes) contributing to their resilience and sustainability?
2. How is AI applied to optimize collection management in art museums?
3. How can AI enhance the visitor experience in art museums to renew interest in art and its context through exhibits and exhibitions?
4. What challenges arise from integrating AI in art museum settings, and how can these be effectively addressed within a human-centered cultural management framework?

The primary tool for data collection was Google Scholar, which provided access to articles from major academic publishers such as ACM, Elsevier, MDPI, SAGE, Springer Nature, Wiley-Blackwell, EDP Sciences, Emerald Publishing Limited, Taylor & Francis (Rutledge), and IEEE, as well as scientific conference proceedings (e.g., MuseWeb and EVA), academic books or chapters. Relevant sources were identified through targeted keyword searches, including combinations such as "AI" AND "museums", "AI" AND "sustainability" AND "museums", "AI" AND "museum operations", "AI" AND "museum collections", and "AI" AND "visitor engagement".

The literature search focused on the last decade (2015–2025), to capture the evolving discourse and experimentation around AI in the museum sector, following its rise in 2015

fueled by technological breakthroughs [32]. Special emphasis was placed on the most recent five years (2021–2025), due to the rapid advancement of GenAI and its innovative applications in art [33].

While peer-reviewed academic literature forms the study's foundation, the fast-evolving nature of AI in museums and the need for a global mapping of AI potential necessitated a multi-layered approach, strategically supplementing scholarly work with carefully curated, practice-oriented sources.

These materials were chosen based on strict criteria for relevance and source credibility. The latter was mainly ensured by selecting references from globally renowned museums, reputable scientific conferences, international institutional bodies, as well as companies that had implemented specific AI applications in museums and trusted media outlets, whose veracity was further reinforced through cross-verification. This ensures the study maintains academic rigor while grounding its theoretical analysis in cutting-edge practice, providing a comprehensive and current understanding of AI's integration in museums.

Therefore, we incorporated institutional and professional sources like museum reports, applied case studies, and consultancy briefings, which offer valuable perspectives on operational realities and experimental applications often not yet reflected in academic publications. To contextualize these developments within broader ethical and strategic frameworks, the study also draws on select policy documents and guidelines from international and regulatory bodies such as ICOM, UNESCO, the OECD, and the EU (e.g., the AI Act). These sources offer critical perspectives on governance, ethical adoption, and definitional clarity within the cultural heritage (CH) sector.

Finally, reputable media coverage—from outlets like *The Guardian*, *The New York Times*, and *Artnet News*—is used to trace the visibility, reception, and societal impact of AI in museums. This real-time documentation, critically integrated alongside academic and institutional literature, grounds theoretical analysis in contemporary developments, real-world applications, and public discourse.

The most significant findings from the literature review, focusing on both theoretical and practical applications of AI in museums, are presented in a visual format (Table A1) to enhance clarity and provide an accessible overview. The table provides a comprehensive analysis of AI applications in museums, outlining their uses, benefits, sustainability impact, challenges, and risks within three key domains of the study: Operational Efficiency, Collection Management, and Visitor Experience. Entries 1–49 draw on 55 sources, with 35 dating from 2021–2025, highlighting the field's rapid recent development.

In addition, Table A1 includes four dedicated sections that thematically group the reviewed literature on Visitor Experience implementations: Chatbots and Virtual Assistants, Recommendation and Personalization Systems, Immersive and Interactive Experiences, and Accessibility and Inclusion Tools (entries 50–53). Remarkably, 28 of the 32 publications supporting these thematic groupings were published between 2021 and 2025, underscoring their contemporary relevance and rapid advancement.

Building on the analysis in Table A1, the benefits of AI implementation within each domain are further distilled and presented in separate tables (Tables A2–A4) to provide a more focused and comparative view. In contrast, the challenges and risks, which are largely cross-cutting and affect all three domains, are consolidated into a single table for clarity and to avoid redundancy (Table A5).

4. AI-Enhanced Operational & Strategic Efficiency

Evolving from a "nice-to-have" to a "must-have," AI now offers museums a competitive edge by enhancing decision-making, planning, and scheduling through advanced analytics in operations, visitor services, and financial management [20,34]. This transfor-

mative impact is also evident in national initiatives in countries like China and Korea, where AI drives the modernization of existing museums and the creation of new ones, from architectural planning to construction [35].

In the realm of museum marketing, AI enables data-driven personalization and strategic outreach, by allowing institutions to analyze visitor data and segment audiences based on demographics and behavior for targeted engagement and customized experiences [36,37]. As Huang and Rust [16] highlight, AI enhances marketing effectiveness by automating routine tasks, processing large datasets for informed decision-making, and analyzing human interactions and emotions, ultimately improving research, planning, and execution across the marketing mix.

Moreover, AI-driven data analytics enhance museum services by analyzing visitor patterns, such as popular exhibits, peak hours, and common pathways, to predict flows, prevent overcrowding, reduce wait times, and optimize educational programs and exhibition layouts for improved visitor comfort and satisfaction [14,37]. Additionally, AI facilitates personalized content and interactive, audience-centered exhibits, transforming museum experiences from static, one-size-fits-all presentations into dynamic, customized, and data-driven engagements [37].

Beyond visitor experience, AI streamlines operations and resource management by analyzing ticketing, attendance, and membership trends, optimizing fundraising efforts, and minimizing e-commerce redundancies [32]. Through efficient resource allocation, and data-informed forecasting, museums can reduce operational costs, and strategically adapt to evolving conditions, thereby supporting long-term financial stability and institutional resilience [36,37].

A notable example is the predictive model developed by the National Gallery in 2019, aimed at estimating visitor numbers and categorizing ticket buyer types (Figure 1). However, based on pre-pandemic data, the model lost accuracy after 2020 due to drastic shifts in visitor behavior caused by the COVID-19 crisis. The museum reverted to traditional statistical methods while initiating the collection of updated post-pandemic data (National Gallery staff, personal communication, May 2025). This case highlights the need for continuous model adaptation and sufficient time investment in gathering high-quality data to ensure the effective use of AI.

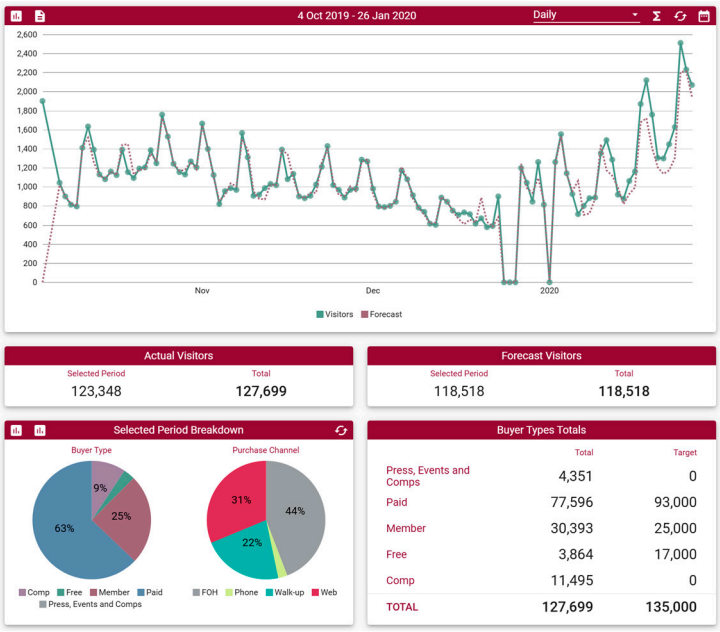


Figure 1. Screenshot of the National Gallery's visitor prediction model. Source: 36. [Courtesy of the National Gallery].

By synergistically applying AI capabilities such as dataset correlation and sentiment analysis [12], cultural organizations optimize internal operations and visitor engagement, fostering efficiency and responsiveness. Leveraging data, such as visitor feedback, behavioral metrics, and chatbot interactions, museums continuously refine exhibits and services, personalize experiences, inform strategic decisions, and adapt offerings to evolving audience interests [34,37].

The Van Gogh Museum in Amsterdam exemplifies this approach, partnering with Eraneos to deploy an AI-powered tool that analyzes roughly 1500 monthly visitor comments in over 100 languages using NLP and ML, categorizing sentiment and themes for actionable insights without requiring in-house AI expertise [38]. Further demonstrating AI's diverse analytical applications, the Museum of Modern Art (MoMA) leverages visitor feedback for signage, The Broad in Los Angeles monitors engagement metrics to streamline operations, and the Art Institute of Chicago (AIC) employs AI to analyze visitor flow and dwell times to strategically tailor exhibitions [39].

As part of broader efforts to optimize both visitor engagement and exhibition design, AI-powered Mobile Eye Tracking (MET), which combines gaze tracking, object recognition, and convolutional neural networks (CNNs), maps visitor attention across artworks and exhibits, optimizes spatial layouts, detects social interactions, and delivers real-time personalized guides, thereby supporting data-informed, visitor-centered curation and evaluation [40–42]. Additionally, AI solutions increasingly bolster art museum security, utilizing facial recognition technology (FRT) for enhanced surveillance and theft deterrence [20].

Furthermore, AI accelerates research by analyzing data for scientific purposes. For example, FRT applied to portraits helps distinguish sitters, identify artistic styles, and resolve identity uncertainties [43], while DL at the Smithsonian accurately identifies plants and fish, reducing reliance on microscopy or DNA testing [44].

In art museums, AI advances authentication by detecting subtle, invisible details for more precise validation [20]. By analyzing high-level features like brushstrokes and aesthetics, it provides objective insights into an artist's signature, supporting attribution efforts at institutions like the Rijksmuseum [39,45]. Additionally, AI tools utilizing CNNs and hyperspectral imaging combat forgery with high precision by replicating expert analyses and improving reliability through multivariate spectral data, even without matching databases [45,46].

Similarly, Frank & Frank [47] proposed leveraging CNNs to create probability maps for attributing works and detecting forgeries, where colors (e.g., red/yellow for Leonardo, blue for other artists) show the creator (Figure 2). Their system deconstructs and reconstructs images using mathematical sequences, generating individual *probability maps* to form attribution hypotheses. Importantly, the authors stress that these computational tools' accuracy and reliability depend on close collaboration with human expertise and connoisseurship, serving as a complement to, not a replacement of, traditional methods [47].

In addition, AI significantly enhances conservation by monitoring artwork conditions, identifying restoration needs, and revealing features for better preservation [20]. It supports artifact reconstruction through digitization, analysis, and visualization via ML and computer vision (CV) [37]. For example, the Smithsonian employs AI-driven predictive maintenance with sensors and ML to anticipate equipment failures, reducing downtime and costs [44]. Similarly, the Van Gogh Museum uses AI to restore faded paintings [38], while the Rijksmuseum combines ultra-high-resolution imaging—such as the 717-gigapixel scan of *The Night Watch*—with analytical tools to detect material changes like pigment degradation and lead soap formation [9,48].

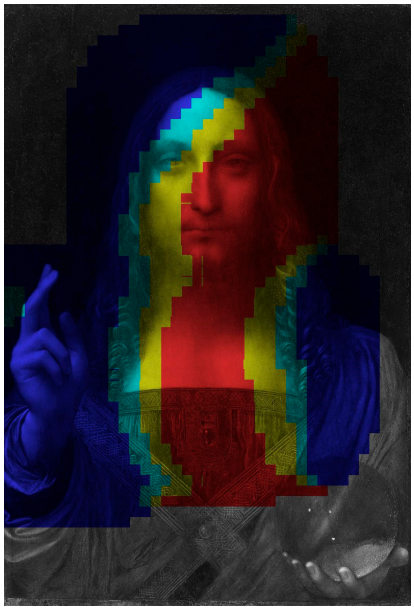


Figure 2. Probability map of Leonardo da Vinci's *Salvator Mundi* (c. 1499–1510) in 350 × 350 tiles. Photo by Steven J. Frank. Source: 47. [Courtesy of Steve and Andrea Frank].

Finally, AI is increasingly reshaping the very core of exhibition development, influencing curatorial practices from conceptualization and design to interpretation and narrative shaping. This evolution enhances accessibility and deepens audience engagement by merging AI's analytical capabilities with human creative insight. A prime example is the *AI Connections Table*—developed at the Henry Ford Museum by Bluecadet and creative technologist Weili Shi—which uses pattern recognition to link artworks and generate thematic content, combining AI-generated insights with curator validation to ensure contextual accuracy, cultural relevance and interpretive depth [49].

In art museums, this approach becomes more experimental and conceptual. In an early 2020 effort, the exhibition *KUNST(re_public)* at HALLE 14—Center for Contemporary Art Leipzig was algorithmically curated using network science and word embeddings. Though coherent and engaging, it lacked a distinct curatorial voice, highlighting both the creative potential and limits of AI [50].

Likewise, at the Nasher Museum of Art, AI was directly involved in curatorial decision-making, using ChatGPT to select works, generate descriptions, and identify thematic links, tasks traditionally performed by curators, ultimately reaffirming the irreplaceable value of human expertise in interpretation and nuance [51]. Additionally, at the Lowe Art Museum's *Fool Me Once* exhibition, AI contributed to both art production, as it generated artworks blended with human-made pieces, and interactive interpretation, challenging viewer perceptions of authenticity and creativity through the display [52,53].

Overall, currently more promising than proven, AI-assisted curation has the potential to flourish within a dynamic human–AI partnership, sparking fresh perspectives, transforming art engagement, and opening new pathways for curatorial judgment and reflection on interpretation, value, and the curator's evolving role.

Conclusively, based on the evidence presented and the data in Table A1, AI enhances key functions such as workflow optimization, resource allocation, museum marketing, security and safety, research, art authentication, conservation, and curation. These advances collectively strengthen operational and strategic efficiency across *Strategic, Administrative and Institutional Management*, *Visitor Management and Exhibition Development*, *Collections Care and Preservation*, and *Scientific Research and Curatorial Innovation*, as detailed in Table A2.

5. AI-Driven Management of Digital Collections: From Tags to Tales

AI technology enhances digital record preservation in art museums by ensuring efficient storage, retrieval, and long-term protection of historical documents and artifacts [20]. Beyond preservation, AI revolutionizes digital collection management through analysis, interpretation, narrative development, contextual insights, and latent space exploration.

Increasingly applied in CH for large-scale image analysis [54], AI streamlines content management and information retrieval by automating metadata tagging for enhanced discovery via visual search and NLP, while also improving asset organization, detecting duplicates, facilitating selection and editing, and ensuring quality through explicit content identification [52,55].

These AI capabilities largely stem from CV advancements, particularly the significant surges driven by ML and breakthroughs in DL and CNNs since the 2000s. This evolution revolutionized image recognition, enhancing applications like exhibit categorization and immersive learning [56–58].

In art collections, AI-generated descriptive text adds value by analyzing themes, visual elements (e.g., color, technique, style), and emotional states in portraiture, identifying expressions that range from solemnity to happiness (Figure 3). This automation transforms untitled or obscure artworks into accessible, searchable assets for curators, researchers, and visitors [18,32,59].

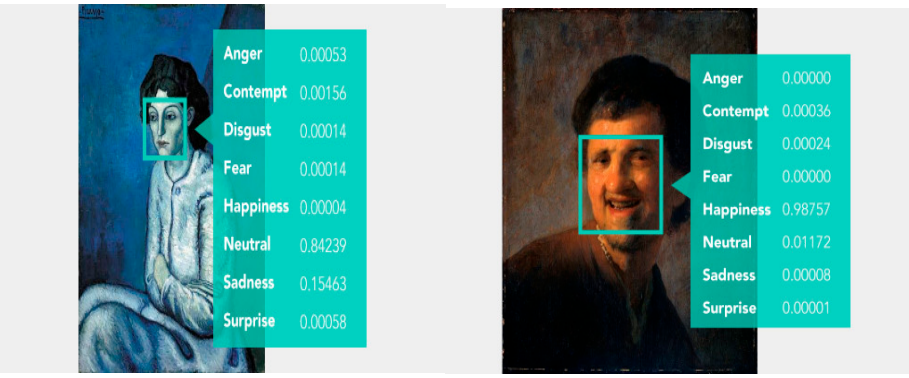


Figure 3. AI analysis of emotions in art, comparing Picasso's *Femme aux Bras Croisés* (1901, private collection), and Rembrandt's *Bust of a Laughing Young Man* (1629, Rijksmuseum). Source: 32. [Courtesy of Brendan Ciecko].

This echoes the Rijksmuseum Amsterdam's *Rijksstudio*, which utilizes ML and color-based image retrieval to enhance visitor exploration and interaction [60,61]. Similarly, since 2016, the Harvard Art Museums have pioneered CV through platforms like IIIF Explorer and AI Explorer (Figure 4), which allow users to navigate their collection with AI-generated tags, captions, and recognition types [18,62]. These tools demonstrate AI's ability to interpret visual art, create new metadata, and provide innovative ways for non-specialists to engage with art collections (ibid.).

Major art museums, including MoMA, The Met, Tate, SFMOMA, Carnegie, the Princeton University Art Museum, and the Smithsonian, along with many European institutions (e.g., German-speaking museums), are increasingly leveraging AI technologies like ML and CV to improve the interoperability, analysis and accessibility of their digital archives and metadata [18,25,63]. Such advancements are especially impactful for institutions with large collections such as the Met, which holds hundreds of thousands of works, by saving experts and researchers' time and resources, while streamlining organization and discoverability through automated tagging and metadata generation in collaboration with data scientists [45,64,65].

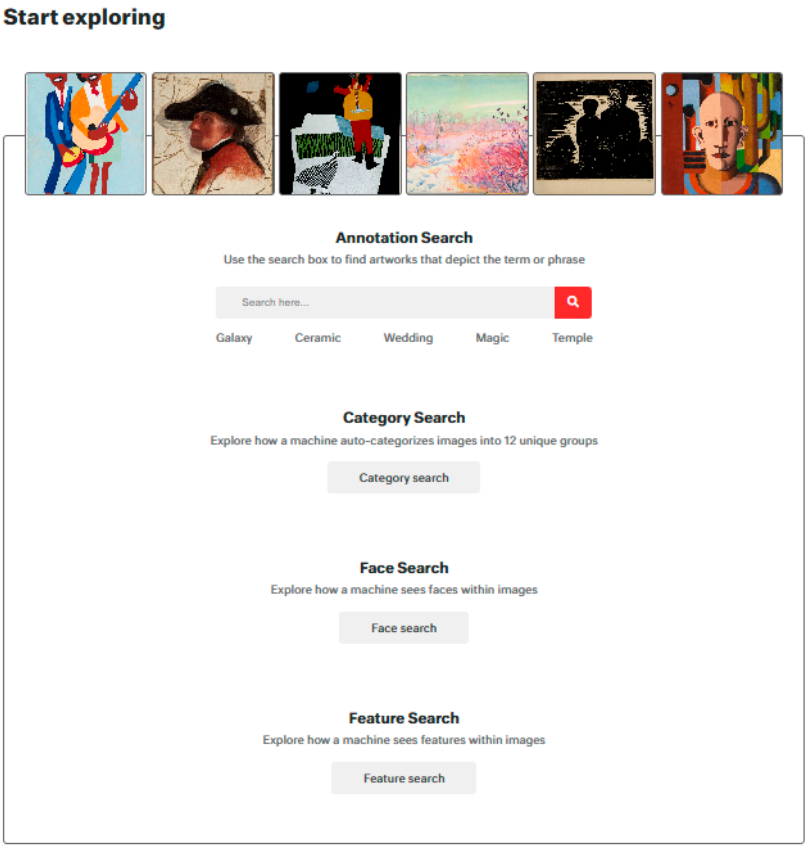


Figure 4. Screenshot from the Harvard Art Museums' AI Explorer. Source: 62. [Courtesy of the Harvard Art Museums].

Innovative approaches integrate ML with semantic reasoning—exemplified by Bobasheva et al.'s [66] enhancement of France's national repository, Joconde—to optimize analysis, improve content-based search, and automate artwork annotation, enriching curatorial knowledge. Semantic AI search refines online collections by emphasizing context and meaning, enabling more intuitive art discovery, as demonstrated by the Norway National Museum [67]. Similarly, the London Museum harness AI not only for descriptive text and inclusive language, but also to reveal deeper, latent relationships between objects and narratives, moving beyond keyword matching toward richer, contextual connections [52].

AI also explores cross-collection insights, revealing cultural and historical connections. The Massachusetts Institute of Technology's (MIT) *MosAIc* algorithm uses DL to identify visual and thematic similarities across mediums, regions, and eras, enhancing art historical understanding by revealing cross-cultural correlations in The Met and the Rijksmuseum collections [68]. Likewise, MoMA and Google apply AI to analyze over 30,000 exhibition photos, linking past exhibitions to current holdings and enhancing cataloging and accessibility [69].

As exploration capabilities push the boundaries of knowledge and imagination, art museums are harnessing AI-driven approaches to redefine engagement, as shown by the Barnes Foundation's use of CV to uncover hidden links between seemingly unrelated artworks [70]. Similarly, The Met, collaborating with Microsoft and MIT, leveraged neural networks to map artworks into latent spaces, generating surreal yet plausible variations between actual and imagined realities [71,72]. Despite their innovation, such initiatives must remain contextually meaningful offering fresh perspectives on CH and enriching art history—lest they be reduced to "nothing more than a few weak software freebies for personal data and unpaid labor" [73].

Continuing these generative explorations, GenAI is also expanding the boundaries of artistic reinterpretation and creative expression. At the AIC, an experimental hackday project employed a browser extension—powered by Replicate's Python interface and the Midjourney diffusion model—to generate alternative versions of collection images from textual prompts and alt text, fostering creative engagement and blurring lines between creation, curation, and audience participation [74].

As AI and large-scale collection data management become increasingly central to both analysis and artistic creation [19], a new postmodern shift emerges that prioritizes the analysis, reinterpretation, and reassembly of accumulated cultural data over the invention of radically new forms [75]. Artists increasingly explore this terrain through GenAI tools like generative adversarial networks (GANs), where intellectual insight, human sensitivity, and machine-assisted imagination converge to open new avenues for reshaping CH.

Notable examples include Jake Elwes's *Latent Space*, Helena Sarin's *Latentscapes*, and Mario Klingemann's *Memories of Passerby* [76]. Similarly, Refik Anadol Studio's *Latent Being*, and *Machine Hallucinations*—including works such as *Unsupervised*—navigate latent spaces to transform vast datasets into immersive, continuously evolving visual and auditory experiences [77–79].

Conclusively, as evidenced in Table A1, AI strengthens the management of digital collections by enhancing functions such as metadata tagging, collection accessibility and searchability, cross-collection analysis, artistic reinterpretation, and AI-assisted art production. Together, these advances support key areas including *Cataloging and Interpretation, Collection Access and Navigation, Creative and Conceptual Exploration*, and *Public Engagement and Cultural Stewardship*, as detailed in Table A3.

6. Optimizing Visitor Experience Through AI

6.1. AI-Powered Chatbots and Visual Assistants

Identified as the most widely adopted museum tool in 2021 (34), AI-powered chatbots have revolutionized museum experiences. They personalize content, recommend artworks, answer visitor inquiries and provide scalable, real-time multilingual support that enhances accessibility and inclusivity for international audiences, breaking down language barriers [37,80]. Since the early 21st century, chatbots have evolved from simple infobots into advanced AI assistants incorporating gamification and interactive engagement [81].

The evolution from basic guidance to more sophisticated interaction tools is exemplified by IRIS+, an AI-powered digital assistant developed at the Museum of Tomorrow in Rio de Janeiro (Figure 5), which fosters deeper engagement and inspires social and environmental action, directly aligning with the museum's core philosophy and objectives [82,83].

Similarly, experiments at the Swedish National Museum and the National Museum of Korea demonstrated that AI chatbots enhance visitor engagement by offering interactive, on demand information, assisting with wayfinding, and creating emotional connections with exhibits. Furthermore, they support learning by adapting content to individual preferences through NL interactions [84,85].

Notable pre-pandemic example of chatbot integration for virtual exploration and visit planning in art museums include the Petit Palais Museum's *Ask Sarah* (2018), which provided information on hours, prices, access, and exhibitions via Facebook Messenger [86]. During the COVID-19 pandemic, museums increasingly leveraged AI for remote audience engagement, such as the AIC's Alexa Conversations-powered voice app for immersive exploration of over 300 artworks through voice commands and categorized audio commentary [87].

For the in-situ experience, early examples include the Akron Art Museum's *Dot* (2018), which provided Facebook Messenger tours and informed future exhibitions [39,88], and

the Pinacoteca de São Paulo's 2017 debut of *The Voice of Art*, which offered immediate, personalized responses to smartphone-based artwork questions [89–91].



Figure 5. Visitors with headphones interact with IRIS+ at the Museum of Tomorrow. Source: 82. [Courtesy of Museu do Amanhã].

CH organizations are also adopting chatbots to create gamified experiences for younger, digitally-savvy audiences, like the Chat Game in Milan's House Museums, where AI characters guide visitors, especially teenagers, through puzzles merging play with cultural education [92,93]. The Musée National des Beaux-Arts du Québec's (MNBAQ) Ask Mona chatbot, offering personalized insights into artwork history via text or voice [94,95], further demonstrated inspiring adoption in over 200 museums, including the Centre Pompidou and the Louvre [96,97].

The use of chatbots extends to virtual interactions with historical figures, leveraging archival records, as seen in The Met's collaboration with OpenAI to create a chatbot representing 1930s socialite Natalie Potter for visitors to explore a historical artifact and the human story behind it [98,99].

6.2. AI-Based Recommendation and Personalization Systems

AI-driven recommendation systems, originally popularized in e-commerce [32], are now widely adopted by online museum platforms to personalize merchandise suggestions based on user preferences, browsing behavior, or purchasing history, enhancing the digital retail experience [100–102]. Often integrated with IoT and data analytics, these systems also elevate on-site experiences through user profiling, real-time tracking, and adaptive content delivery, offering tailored suggestions, navigation assistance, personalized tours, interactive exploration, and immersive storytelling, aiming to enhance accessibility, engagement, and visitor satisfaction [11,20,32,37,52,63,103,104].

Conversely, *anti-recommendation* systems broaden user perspectives by intentionally diverging from past preferences and familiar content, mapping unexplored exhibits to promote serendipitous discoveries and encourage open-ended exploration [105].

Reinforced by AI recommendation systems, audio guide apps and artwork analysis platforms are transforming the museum experience. Notable examples include Cheng Shiu University's Automatic Exhibition Guide System [17], which uses FRT and real-time tracking for tailored content delivery, and the Hilversum Media Museum's AI-driven personalization based on visitor profiles, such as photo, email, and preferences [96,106–108].

6.3. AI-Driven Immersive and Interactive Experiences

Museums are embracing AI to create immersive storytelling and cutting-edge interactive experiences that blend art, technology, and public engagement. This includes AI-generated virtual artwork records, facilitating immersive 3D modeling, tours, and Augmented Reality (AR) experiences, that allow exploration of artworks from various angles and lighting conditions [20].

Advanced AI-based applications combine conversation, storytelling, avatar design, and multimedia to deepen engagement and emotional resonance. Deepfakes exemplify this trend transforming passive observation into interactive experiences, as demonstrated in the Dalí Museum's *Dalí Lives* exhibit in Florida [109]. This AI installation uses ML and CV to recreate Dalí's voice, expressions, and movements—trained on archival footage and mapped onto a performer—enabling visitors to interact with a lifelike virtual Dalí through selfies and conversations (Figure 6), fostering immediacy, emotional connection, and amusement [110–112].



Figure 6. Screenshot of digital Dalí at the *Dalí Lives* exhibition, created in collaboration with Goodby, Silverstein & Partners (GS&P), at The Dalí Museum, St. Petersburg, Florida. Source: 110. [Courtesy of Goodby Silverstein & Partners].

Similarly, the *Hello Vincent* (*Bonjour Vincent*) project at the Musée d'Orsay's 2024 "Van Gogh in Auvers-sur-Oise" exhibition featured an evolving AI chatbot that simulated conversations with Van Gogh based on 900 of his letters (Figure 7). Developed over eight months by the Paris-based tech firm Jumbo Mana, the avatar served as a cultural mediator, offering a personalized and immersive experience that deepened visitor engagement with the artist's life and work [113,114].

Other examples of active visitor participation include Hofmann and Preiß's *Wishing Well* (2022–2023), developed through a collaboration between ZKM–Center for Art and Media Karlsruhe and Deutsches Museum Nuremberg [115]. This Duchamp-inspired installation used AI to transforms spoken wishes into images (Figure 8), turning prompt engineering into a participatory artistic act and fostering human–AI co-creation while highlighting ethical questions about data bias and artist consent (ibid.).

Another example is the MIT Museum's *Collaborative Poetry* (2022), an installation by Bluecadet and Weili Shi (Figure 9). Powered by OpenAI's GPT-3, it empowered visitors to co-create poems with a neural network, which were then displayed on curving overhead screens cultivating an ongoing human-machine creative dialogue [116–119].



Figure 7. Screenshot from the *Bonjour Vincent* application, developed by Jumbo Mana at the Musée d'Orsay's "Van Gogh à Auvers-sur-Oise" exhibition. Source: 113. [Courtesy of Jumbo Mana].



Figure 8. Yannick Hofmann, *Wishing Well*, 2022–2023. Installation view in *the intelligent.museum is around the corner* exhibition (ZKM | Karlsruhe, 2023) © intelligent.museum. Photo: Felix Gruenschloss. Source: 115. [Courtesy of ZKM | Center for Art and Media Karlsruhe].



Figure 9. Bluecadet's application *Collaborative Poetry*, 2022. Photo: Dan King. Source: 118. [Courtesy of Bluecadet).

In the same vein of encouraging active visitor participation, the Dubai Art Museum animated visitors' scanned drawings onto a stage [120,121], while the Van Gogh Museum, in collaboration with Dutch consultancy Magnus, implemented an AI-powered portrait generator, which converted visitor selfies into Van Gogh-style paintings [122].

Furthermore, the *Music Walks* project at the Museum Barberini in Potsdam (Figure 10), developed with composer Henrik Schwarz and supported by the Hasso Plattner Institute, combine AI audio engines with smartphone sensors to generate adaptive soundscapes that heighten the emotional impact of the museum's Impressionist works [123,124].



Figure 10. Screenshot: Visitors using the *Music Walks* app at the Museum Barberini. Photo: Sebastian Bolesch. Source: 124. [Courtesy of Museum Barberini].

6.4. AI-Enchanced Accessibility and Inclusion Tools

AI is revolutionizing online museum experiences by enhancing educational outreach and making exhibits more engaging and accessible [9]. Institutions like the British Museum, the Smithsonian, and the Louvre exemplify this by customizing content and boosting accessibility through virtual guides, image recognition, immersive technologies, and multilingual support, while refining visual design with adaptive interfaces and intelligent algorithms that seamlessly integrate virtual elements for greater coherence [125,126]. The Prado Museum's FrAI Angelico project further exemplifies inclusive innovation, utilizing AI to analyze and describe artworks, offering tailored tours for visually impaired visitors, and supporting art research [127,128].

Additionally, AI-powered sensory technologies, such as holographic nano-touch membranes and ultrasonic haptic feedback, enhance virtual engagement by permitting users to feel virtual shapes and interact tactilely with simulated environments [13]. Likewise, sensor-driven haptic and interactive AI devices, supported by ML and databases, deliver personalized, multi-layered content that significantly amplifies visitor understanding, satisfaction, and engagement time in museums compared to traditional technologies, as indicated by a comparative analysis of visitor engagement [14] (Figure 11).

In conclusion, AI-powered visitor experiences, as examined across the four subdomains discussed above, enable museums to strategically enhance key functions, including *Visitor Assistance and Navigation*, *Interaction with Chatbots and Virtual Assistants* such as historical personalities, *Personalized Recommendations*, *Immersive and Edutainment Experiences*, as well as *Co-creation and Contributions to Art*, while boosting *Accessibility and Inclusion*, as demonstrated in Table A4.

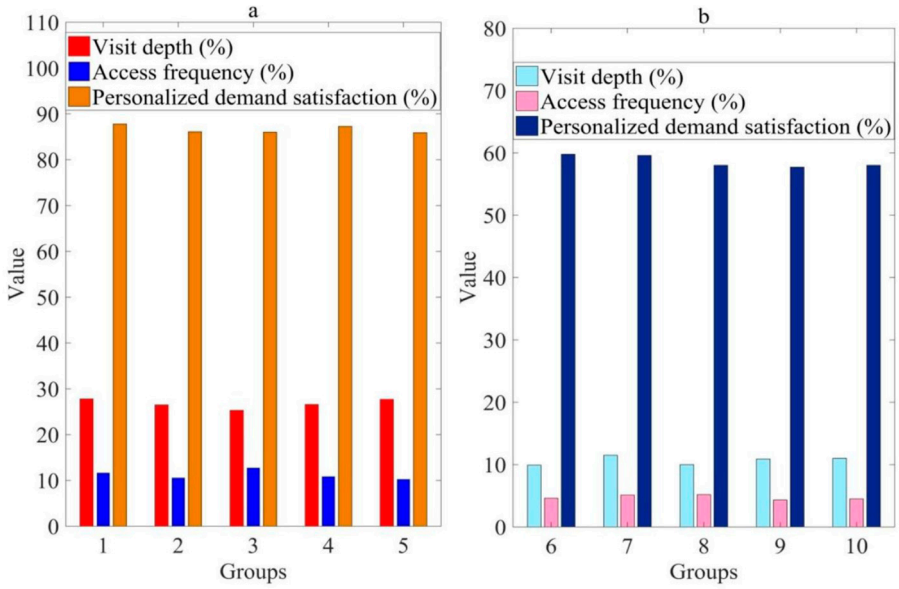


Figure 11. Visitor engagement with an AI-powered recommendation system (**a**) and a traditional museum layout (**b**). Source: 14.

7. Navigating Challenges with a Human-AI Compass

As discussed in previous chapters, AI applications in art museums are rapidly expanding, benefiting key functions and overall museum operations, yet they remain fraught with significant challenges that permeate all museum domains and the broader social context in which they operate. Some challenges are domain-specific, for example, algorithmic errors and misclassification in Collection Management due to the complexity and multifactorial nature of cultural content, or privacy and consent concerns arising from visitor-tracking systems in Operational Efficiency and Visitor Experience. However, most challenges are cross-cutting and can be grouped into four main areas—Technical-Operational, Ethical-Governance, Environmental and Socioeconomic-Cultural (Table A5)—which are examined in this chapter.

Financial and logistical barriers such as high implementation costs, ongoing infrastructure demands, staff training, time investment, and limited in-house expertise often hinder widespread adoption [17,20,25,32,41,52,80]. As a result, experimental initiatives—like the aforementioned *Voice of Art*—frequently remain fragmented or short-lived due to budget limitations, highlighting the need for sustained funding and long-term strategic planning to support continuous innovation [91].

Beyond operational and strategic challenges, AI-driven applications also face notable technical and performance hurdles. Among these are the need for advanced chatbot training to handle diverse and nuanced visitor queries, and the shortcomings of current 3D modeling tools in conveying artistic depth and achieving real-time responsiveness [97,117].

Hardware and software limitations further hinder AI performance, necessitating ongoing technological improvements for smoother integration. Furthermore, data integrity issues—such as inconsistencies or inaccuracies in the underlying information—pose a significant challenge [13,36,44]. Even minor inaccuracies in human annotations, for instance, can significantly skew ML accuracy [66].

Moreover, while ML models excel at pattern recognition via bottom-up analysis of low-level features like pixels or tokens, they often lack holistic contextual understanding, which constrains their capacity to build complex representations or derive meaning in the way human cognition can [59]. GenAI adds new challenges, most notably through

hallucinations—instances where models confidently produce incorrect or fabricated content as if it was factual [80].

These reliability concerns are especially visible in CV's struggle to interpret symbolic elements and historical context. Notable misinterpretations—such as the misidentification of young boys in dresses as girls at The Met [65]—or the *FrAI Angelico* project's erroneous identification of mobile phones in Renaissance paintings [116], illustrate the need for deeper cultural awareness in AI systems.

Similarly, AI-powered chatbots used in interactive guides and gamified experiences often fail to maintain contextual awareness, emotional sensitivity, and alignment with art museums' pedagogical goals [92]. The inherently rich and multifaceted nature of art intensifies implementation complexity [20]. In fields like art authentication and interpretation, AI's effectiveness remains limited without human support, still lacking the conceptual depth and nuance offered by human expertise [20,32,47,65,116].

Equally critical are the ethical concerns surrounding AI in cultural institutions, which risk compromising fairness, inclusivity, and accountability. Key issues include algorithmic biases such as cultural misrepresentation or gender stereotyping that may result in offensive outputs or the erasure of minority voices [37,44,52,63,80,129] as well as ambiguity around copyright and ownership of AI-generated content, unclear lines of responsibility, and philosophical questions regarding human creativity, humanness, and the essence of being [28].

Particularly within art museums and painting collections, AI systems trained on existing datasets and built on opaque algorithms risk reinforcing discriminatory language, Eurocentrism, and entrenched patriarchal, colonial, and capitalist power structures, undermining accountability, and public trust [55]. To counter this, museums are urged to adopt a critical, transparent, and socially conscious approach that prioritizes equity over mere efficiency. This includes embracing data solidarity, openly sharing datasets, and aligning AI practices with critical social research and movements to challenge, rather than perpetuate, systemic bias (ibid.).

Inclusivity and accessibility gaps further complicate implementation. For instance, the Pinacoteca de São Paulo's AI chatbot, which operated solely in Portuguese, inadvertently excluded Brazil's deaf community, whose primary language is Libras (Brazilian Sign Language) [90].

Ethical concerns also arise from collaborations between major museums and tech companies, raising questions around brand alignment, mission integrity, and the risk of *brandwashing*. As Villaespesa and Murphy [36] argue, museums must apply the same ethical scrutiny to tech partnerships as they do to donor relationships, to protect their mission and public trust.

AI adoption also presents serious privacy and security concerns, inherent in the collection and storage of personal data [37]. The increasing use of AI systems with real-time geolocation and FRT poses acute risks for vulnerable populations like children [80] and necessitates robust data protection measures, including encryption, secure networks, access controls, ethical consent, and transparent privacy policies to safeguard visitor information, prevent misuse, and maintain trust [20,37,43]. Even when legally permissible, such technologies can be ethically questionable, requiring museums to consider professional standards alongside the law [36].

Environmental impact is another critical concern. The high energy demands of training large AI models contribute to significant carbon emissions and resource depletion. These environmental issues are compounded by broader socioeconomic injustices and labor exploitation, notably the precarious working conditions for miners extracting rare minerals

for AI hardware and the low-paid, often outsourced data labeling work in developing countries [59,130].

In terms of societal implication, especially regarding human relationships and social dynamics, museum professionals and researchers warn that AI tools could overstimulate visitors or disrupt meaningful interactions within the museum environment, potentially diminishing the authenticity of museum experience [80,129]. These apprehensions mirror broader safety test findings indicating that users can form strong emotional attachments to AI, leading to possible addiction, emotional dependency, and associated psychological and ethical risks [52].

Furthermore, technocentrism risks limiting AI's potential as a force for sustainability and inclusivity [17,131]. Overreliance on technological solutions driven by corporate marketing, geopolitical rivalries between powers like the US and China, and concentrated control in elite tech hubs like Silicon Valley poses major challenges to the inclusive and critical use of AI in museums [130].

Given these profound challenges, viewing AI through a behavioral lens is crucial, as it shifts the focus from AI as a mere technological tool to its profound influence on human experience, psychology, and social interaction [132].

In response to these impacts, scholars advocate for museums to engage openly and accountably with AI's societal impacts by offering public programs that promote transparency, critical dialogue, and ethical reflection on emerging technologies [36]. As trusted public institutions, museums are uniquely positioned to advance AI literacy by enabling visitors to actively explore and demystify the technology's black box, through experiential learning and critical engagement with issues such as accountability, authenticity, and diversity [18,59].

By promoting AI ethics education, and active participation in governance, museums can lead the ethical and sustainable adoption of AI in culture. Such ethical governance entails leveraging their high-quality cultural data and embracing soft ethics public discourse to shift from experimental to strategic AI adoption, aligning technological advancements with human-centered values and the long-term heritage preservation goals [25,80].

In this light, AI implementation becomes not merely a technical upgrade, but a strategic institutional decision, as the greatest obstacles to full adoption are cultural rather than technological. Successful integration requires a shift in mindset, redesigned processes, and careful management of the human and ethical dimensions of this transformation [34,118,133].

This proactive museum role is vital, as, according to Bunz [59], AI's overwhelming complexity—rooted in technical, ethical, environmental, and socioeconomic challenges—often deters critical engagement. This vacuum allows profit-driven interests to dominate, risking the undermining of public infrastructure and democratic values, the exclusion of citizen participation, and the surrender of AI's future to those motivated by financial gain. Hence, critique must evolve into an active, participatory, and collaborative practice that unites scientists, artists, citizens, and institutions to collectively shape AI as a force for societal good [59].

This approach also requires interdisciplinary expertise—particularly from the humanities—and collaboration among art history, social studies, and computer science, to support ethical implementation, social fairness, and the creation of explainable AI applications [55,133,134]. Employing diverse datasets, ethical AI frameworks, and staff training can further enhance fairness and inclusivity [37,130].

Ultimately, this evolving role situates museums as democratic spaces of resistance and reflection. As Sterling [135] observes, in a world gripped by a 'polycrisis' of authoritarian resurgence and the erosion of democratic values, museums must actively uphold princi-

ples like diversity, inclusion, participation, sustainability, and justice to help resist global democratic backsliding.

Successfully navigating AI challenges in museum requires robust human oversight, interdisciplinary collaboration, high-quality and inclusive datasets, as well as close human–AI integration. The necessity of human verification for all AI-generated content is crucial to avoid homogenization of knowledge. More broadly, the human-centric approach calls for recognizing AI as a set of advanced algorithms necessitating that museums critically assess input and output data to ensure alignment with museum mission [25,36]. Prioritizing this mission, identity, and curatorial vision over mere technological novelty, remains a prerequisite to ensure educational and cultural integrity [129].

Within this context, the Human-AI Compass provides a conceptual framework for the responsible and sustainable integration of AI in the museum sector. This collaborative system positions AI as the compass's magnetic needle, a powerful instrument that processes vast datasets and algorithms to indicate a specific direction and propose potential routes (Figure 12). The human user acts as the compass holder, equipped with critical judgment, lived experience, and empathy. The human defines the ultimate destination and charts the final course, guided by the museum's true north-the vision for a sustainable museum of the future, grounded in its core human values, ethical governance, and mission-driven direction. This ensures that technological advancements serve both institutional missions and the public good.

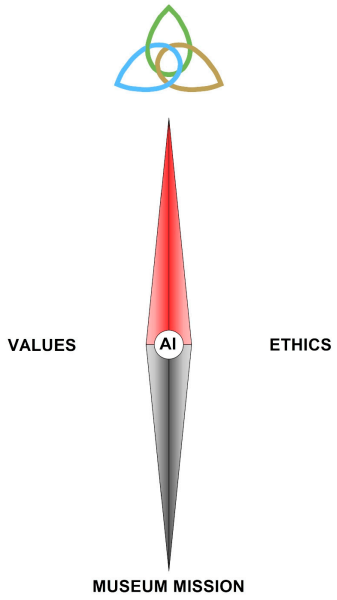


Figure 12. Schematic diagram of Human-AI compass (Created by the authors).

Oriented toward the pillars of holistic sustainability—including operational efficiency, collection guardianship and leveraging, and visitor experience enhancement—this partnership helps museums navigate a course toward a future that is not only innovative and efficient, but also culturally meaningful, socially inclusive, and ethically grounded. This framework seeks to fully leverage technology for maximum economic and social effectiveness while simultaneously promoting human autonomy, creativity, and development, thereby deepening the cultural and spiritual impact of this unique symbiosis.

8. Results-Discussion

The literature review on AI integration in museums highlights its broad application across multiple functional areas. AI supports a wide array of museum activities—from

collection preservation, research, and curation to interpretation, display, and collections management, and from marketing, fundraising, and administration to public engagement, education, and even art creation—demonstrating its pervasive and growing role in the sector (Tables A1–A4).

AI plays a key role in enhancing museums' economic sustainability by optimizing operations, improving efficiency, and reducing costs. By automating and streamlining core functions—such as visitor flow, staffing, ticketing, exhibit management, cataloging, and visitor services—AI enables more effective resource allocation and significantly lowers operational time and overheads.

These efficiencies not only improve internal workflows but also enhance visitor satisfaction and engagement. In turn, this can lead to increased attendance, memberships, and revenue—key pillars of a sustainable and resilient business model. As museums adapt to changing cultural and technological landscapes, AI empowers them to operate more cost-effectively, respond to audience needs, and ensure long-term financial viability (Table A1: 2–4, 6, 12–16, 18–20, 26–27, 31–37, 39, 43, 47, 49).

Beyond economic benefits, AI also contributes to environmental sustainability by improving resource efficiency, accelerating digital preservation, reducing waste, conserving resources, and minimizing reliance on printed materials. While not directly explicit in the examined literature—a significant gap that represents a missed opportunity to fully understand and leverage technology for sustainable museum operations—AI's environmental sustainability contributions are often implicitly supported by its capacity for optimization and digital transformation.

However, AI's primary and most profound contribution to museums lies in their inherent domain of cultural sustainability, where it strengthens heritage preservation, broadens access, and encourages active participation. It supports cultural conservation and research, deepens exploration and visual storytelling, and fuels creativity, delivering personalized, immersive experiences through intelligent navigation, recommendations, and real-time interaction (Table A1: 1–53). As a result, AI helps safeguard art and CH, increases its visibility and educational value, and makes it more navigable to both researchers and the public. It also expands audience relevance, particularly among younger generations, while reinforcing institutional identity and cultural branding.

Finally, AI advances social sustainability, by enhancing accessibility for all—including individuals with disabilities—through features like audio descriptions and personalized guidance. It fosters community engagement via interactive tools, facilitates global connections and supports collaborative, lifelong learning. Additionally, AI promotes social awareness, broadens inclusive access to CH, and encourages mindful, stress-reducing practices, collectively contributing to a more informed, engaged, and connected society (Table A1: 2, 4, 8–9, 11, 13, 15–18, 21, 25, 26, 28, 30–35, 37–44, 46–53).

This aligns with the evolving role of museums, increasingly recognized as *welfare hotspots*, *gateways to social cohesion*, and *facilitators of sustainability*, as they redefine their mission and purpose [136,137]. Reflecting this shift, museums are transforming from static *temples*, where visitors passively admire artifacts, to dynamic *forums* of knowledge, serving as interactive spaces for intercultural dialogue, critical reflection, and engagement with contemporary issues [138], a transformation further supported by emerging, cutting-edge technologies [139]. Ultimately, being socially engaged—and thus mobilizing both individual and collective intelligence—is a defining feature of modern museum smartification [140].

While AI's assistive capabilities are vast and its creative potential as boundless as human imagination, its integrations in museums presents a range of complex challenges that demand thoughtful solutions (Table A5). The study identified key Technical-

Operational, Ethical-Philosophical-Governance, Socioeconomic-Cultural and Environmental risks, which call for immediate and effective human action to address them.

For AI to fully benefit museums and cultural institutions, scholars emphasize the critical need for clear regulatory and ethical frameworks to guide its responsible implementation, as current legislative infrastructure remains insufficient [18]. Recognizing this gap, global communities and cultural organizations are actively developing strategies to address it.

Key initiatives include AI4People's ethical framework [141] which proposed five guiding principles—*beneficence, non-maleficence, autonomy, justice*, and *explicability*—for a "Good AI Society," and the IEEE's Ethically Aligned Design principles [142]. On a broader scale, UNESCO's Recommendation on the Ethics of Artificial Intelligence **[143]** provides a global blueprint prioritizing human rights, fairness, and accountability.

Regionally, the EU's *AI Act* [144]—the first comprehensive AI regulation—establishes a general framework that adopts a risk-based regulatory approach with horizontal principles for the responsible AI development across all sectors. In the same vein, the Alan Turing Institute's SAFE-D Principles—focusing on *Sustainability, Accountability, Fairness, Explainability,* and *Data stewardship*—offer practical guidance for responsible AI throughout a project's lifecycle [80,145], while the Museums Association's guide specifically addresses ethical AI integration in museums, addressing *transparency, data quality*, and the *mitigation of historical biases* such as colonialism [146].

While not sufficient on their own to fully address the complex challenges posed by AI's integration into our everyday cultural expression and lives, such frameworks and regulations are nonetheless essential. They provide a vital foundation and a necessary first step in navigating this evolving landscape—one that must remain firmly guided by human values and ethical responsibility. At the same time, conceptual models like the Human-AI Compass become invaluable, as they offer a mental model for action and self-governance in a complex, unregulated space, ensuring that progress aligns with a museum's mission and ethical responsibilities.

Despite recurring waves of hype, AI—born of human intellect—learns, imitates, and is destined to surpass us in numerous ways. Yet, it lacks the depth of human experience and the innate perception of the world. At this stage, AI is emerging as a new communication language, gradually woven into daily life, scientific progress, and artistic expression. As we shape and refine this language, our relationship with it reflects our worldview and vision for humanity's future.

In this context, the synergy between ML algorithms and human insight is crucial for ensuring accuracy, reliability, and a human-centered perspective. This balance is especially critical in art museums, where curatorial judgment, historical awareness, cultural sensitivity, and multi-dimensional interpretation are key to preserving the integrity and meaning of cultural narratives and symbolism.

9. Conclusions

AI technologies are revolutionizing art museum operations by enhancing administrative management, and exhibition optimization. They support strategic planning and advance core technical and scientific functions such as conservation, authentication, and curation. At the same time, AI fosters adaptive, audience-centered practices that strengthen institutional resilience and sustainability across all areas of museum operations.

AI also streamlines collection management and analysis, improving organization, accessibility, searchability, connectivity, and learning potential. Furthermore, it expands the boundaries of artistic creation. By increasing productivity and reducing waste, time, and costs, AI can play a vital role in promoting sustainable practices in the management and development of museum collections.

In parallel, AI is reshaping the museum experience itself, making it more dynamic, interactive, and personalized. This drives greater visitor engagement, satisfaction, and attendance. Acting as a knowledge mediator, educational tool, and curatorial assistant, AI fosters deeper audience connections, stimulates intellectual curiosity, and enables immersive, reflective experiences through storytelling, exploration, and co-creation.

However, the implementation of AI in art museums remains fragmented and largely experimental. Its advancement is constrained by a range of hurdles, including operational and strategic limitations, significant ethical and socioeconomic concerns, philosophical and environmental risks, and persistent technical challenges—particularly in maintaining contextual accuracy and cultural sensitivity. As AI becomes an increasingly central communication tool, its integration must align with a museum's overarching strategy. This integration should be guided by human-centered design, strategic foresight, responsiveness to diverse audiences, and continuous human oversight.

While AI continues to evolve and emulate aspects of human capability, it remains fundamentally distinct from human nature. Unlocking its powerful assistive and creative potential in the cultural sector depends on synergistic collaboration with human expertise. This synergy helps prevent new barriers and ensures that AI contributes meaningfully to a sustainable, participatory future that deepens engagement with art and CH while honoring their complexity and richness.

Ultimately, the full and safe realization of these benefits requires a guiding conceptual framework. Anchored in responsible governance, cultural sensitivity, and a commitment to the museum's mission and public trust, a Human–AI compass should continuously orient the operation of a fully sustainable museum of the future, ensuring it upholds human values, preserves the symbolism and depth of cultural interpretation and enriches the evolving dialogue between technology and the arts.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. AI in Museums—Benefits, Challenges, and Sustainability Impact.

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
1	[43]	FRT enables quantitative analysis, sitter identification, artist style characterization, objective feature comparison, and statistically robust research in art collections.	Cultural sustainability	Operational Efficiency	Scientific Research	FRT	FRT in art is challenged by artistic distortions, limited data samples, and the influence of stylistic conventions.	Technical/ Operational Limitations (Misclassifications; Attribution Challenges)
2	[32]	AI aids in analyzing and categorizing collection data. CV improves object identification, pattern recognition, and sentiment analysis. It optimizes ticketing, attendance prediction, membership engagement, and fundraising. It enhances e-commerce through personalized recommendations.	Cultural/economic/ social sustainability	Operational Efficiency Collection management	Resource Management; Automated Cataloging	CV; Data Analytics; Object Identification; Pattern Recognition; Sentiment Analysis	Requirements include substantial resources, time, tools, and expertise for data structuring and system training.	Implementation/ Operational Risks and Socioeconomic Risks (Resource Requirements)

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
3	[44]	At the Smithsonian, AI accelerates botanical research by using DL to identify specimens, detect contamination, and differentiate similar species—streamlining data sorting and allowing scientists to focus on complex research, enhancing productivity.	Economic/cultural sustainability	Operational Efficiency	Scientific Research (Specimens Identification)	DL	Opaque decision-making, hard-to-verify outcomes and limited effectiveness in complex genetic analysis, requiring further refinement for broader scientific use.	Technical Risks
4	[64]	Google's BigQuery dataset of The Met's public domain artworks enabled advanced image analysis via Cloud Vision API—supporting tasks like recognition, color sorting, and landmark detection—to improve metadata, enhance digital access, and optimize collection management.	Cultural/social/economic sustainability	Collection management	Collection Navigation; Digital Access	CV; Color Sorting; Landmark Detection; Metadata Improvement		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
5	[76]	AI exploration of latent space reveals hidden visual possibilities, enabling smooth shifts between abstraction and realism and expanding creative potential in machine-generated art.	Cultural sustainability	Collection management	Artistic Reinterpretation; Creative Production	GenAI; Latent Space Explorations	AI art faces challenges in controlling outputs, balancing human and machine creativity, managing tensions between large-scale models and artistic control, and adapting to rapid technological change. It also challenges traditional concepts of authenticity, authorship, and originality, requiring ethical, explainable, context-aware results and ongoing long-term maintenance.	Technical/ Operational Risks; Ethical/ Philosophical Risks
6	[39]	AI at museums like MoMA, the Broad, and AIC analyzes visitor data to optimize exhibitions, improve ticket distribution, and boost engagement.	Cultural/economic sustainability	Operational Efficiency	Visitor Management; Experience Optimization	Data Analytics; Predictive Modeling		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
7	[70]	AI uncovers surprising links between unrelated artworks, broadening perspectives and deepening understanding of collections.	Cultural sustainability	Collection management	Conceptual Exploration; Collection Interpretation; Knowledge Discovery	CV; Pattern Recognition; Similarity Analysis	Challenges in AI-driven art interpretation include frequent misclassification, limited contextual and historical understanding, tension with curatorial authority due to disparities between human and AI perspectives, and disruption of traditional notions of artistic intent and expertise.	Technical Risks; Ethical/ Philosophical Risks
8	[83]	The Museum of Tomorrow's IRIS+ system uses AI to personalize visitor interactions, promote social and environmental initiatives, enhance accessibility, and continually improve engagement through data analysis, for more tailored experiences.	Social/environmental sustainability	Visitor Experience	Experience Personalization; Visitor Engagement	Data Analysis		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
9	[72]	AI analyzes a diverse artwork dataset and generates imaginative variations, expanding creative possibilities. Through open data, it fosters global engagement with art via innovative digital tools.	Cultural/social sustainability	Collection management	Conceptual Exploration	Open Data		
10	[54]	AI improves searchability of large image collections by enhancing metadata and optimizing information retrieval.	Cultural sustainability	Collection management	Content Management; Information Retrieval	Metadata Enhancement	Difficulties include managing data ambiguity, ensuring precision, and achieving context-specific customization.	Technical/ Operational Risks
11	[105]	Anti-recommendation systems promote discovery and serendipity, exposing visitors to diverse content and enriching cultural experiences by reducing echo chambers.	Cultural/social sustainability	Visitor Experience	Knowledge Discovery	Anti-recommendation systems		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
12	[12]	AI enhances visitor experiences with personalized recommendations and interactive assistance, while streamlining collection management through clustering and automating repetitive tasks.	Cultural/economic sustainability	Operational Efficiency; Visitor Experience	Strategic Planning; Visitor Engagement	Recommendation systems;, Clustering; Automation	Requires accurate, representative data and clear task definitions; integrating AI into museum workflows remains complex.	Technical/ Operational Risks
13	[65]	The Met's Open Access program and public API allow developers and researchers to interact with its collection data, enabling innovations like training CV models for artwork tagging.	Cultural/social/economic sustainability	Collection management	Automated Cataloging (Artwork tagging); Digital Access; Data Sharing	CV; API-based Data Access	Art interpretation subjectivity, limited training data, diverse collections, and gender identification complexity.	Technical Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
14	[63]	AI improves object discoverability and cataloging by enriching metadata and accelerating large dataset analysis, enhancing research efficiency and visual interpretation.	Cultural/economic sustainability	Collection management	Collection Navigation; Digital Curation; Research Enhancement	Data Analysis	Risk of bias (gender, cultural inaccuracies) and offensive outcomes; requires careful monitoring for ethical, accurate AI use in cultural contexts.	Ethical/Social Risks
15	[40–42]	Integrating AI with MET in museums enhances data analysis, personalizes visitor experiences, optimizes exhibit design, and detects social interactions, delivering insights that boost engagement and streamline operations.	Cultural/social/economic sustainability	Operational Efficiency	Operations Management; Exhibition Optimization;	Data Analysis; Social Interaction Detection	Current eye-tracking systems face technical limits. MET systems struggle with cost and accuracy in dynamic settings.	Technical/ Operational Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
16	[36]	AI provides solutions to museum challenges through efficient data analysis, accurate attendance forecasting, and metadata creation. It supports strategic planning in pricing, marketing, and operations, driving audience growth and engagement. Partnerships with tech companies grant access to advanced tools.	Cultural/economic/ social sustainability	Operational Efficiency	Strategic Planning (Museum marketing; Audience Development); Visitor Management; Resource Management	Predictive Analytics; Automation	Ethical and governance concerns include questionable practices, brandwashing, and lack of regulation. Data and algorithmic issues involve bias and insufficient training data. Operational challenges require human oversight, mission alignment, transparency, public programs, and balancing commercial goals with scholarship and critical dialogue. Predictive models require continuous retraining; outdated or biased datasets reduce accuracy, as demonstrated by the National Gallery's visitor forecasting model.	Technical Risks; Operational Risks (e.g., Data and Model Integrity) Ethical/Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
17	[49]	AI uncovers new connections between museum objects, complementing curation and enriching the narrative, while making complex themes accessible to diverse audience and enhancing engagement.	Cultural/social sustainability	Visitor Experience; Operational Efficiency	Exhibition Development (Knowledge Discovery; Curatorial Enhancement; Audience Engagement); AI-Assisted Curation	Network Analysis; Content Analysis; Narrative Interpretation	Balancing human and AI roles alongside AI's physical limitations.	Technical/ Operational Risks; Ethical/ Philosophical Risks
18	[125]	Integrating AI in smart museums enables intelligent, human-centered displays that boost engagement and accessibility. It streamlines exhibit layout, route planning, and real-time audience analysis for precise artifact presentation.	Cultural/social/ economic sustainability	Visitor Experience; Operational Efficiency	Audience Engagement; Exhibition Development; Operations Management	Data Analysis; Predictive Analysis	AI-driven 3D modeling may lack artistic nuance, while optimization algorithms require refinement for real-time precision and fluid interaction.	Technical Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
19	[46]	AI enhances painting and calligraphy authentication by combining hyperspectral imaging with CNNs for faster, more accurate forgery detection.	Cultural/economic sustainability	Operational Efficiency;	Art Authentication	Hyperspectral Imaging; CNNs		
20	[34]	AI modernizes visitor experiences through personalization and NLP chatbots, enriches education through interactive storytelling and feedback analysis, and enhances operational efficiency via visitor flow prediction and resource allocation. It supports data-driven decisions, improves knowledge management through integrated learning frameworks, and provides security and behavioral insights via visitor tracking and social interaction mapping.	Cultural/economic sustainability	Operational Efficiency; Visitor Experience	Strategic Planning; Security & Safety; Operational Efficiency; Visitor Engagement; Interactive Education & Learning;	Predictive Analytics/Forecasting; Data Analysis/Data Mining, Behavioral Analytics; NLP Chatbots;	Key challenges include ethical concerns, the need for strategic AI integration, process redesign, financial constraints, staff mindset shifts and skill gaps, and the technical complexity of integrating Big Data, ML, NLP, and neural networks.	Ethical Risks; Implementation/Operational Risks; Cultural Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
21	[13]	AI-powered digital design enables museums to create visually compelling and aesthetically pleasing spaces. AI enhances the interactive experience of museum visitors, allowing them to engage more deeply with the cultural content, creating a more immersive and participatory learning environment.	Cultural/social sustainability	Visitor Experience	Digital Design; Interactive Engagement; Immersive Experiences; Interactive Education	AI-Powered Digital Design; GenAI	Requires ongoing hardware and technological advancements for optimal performance and integration.	Technical/ Operational Risks
22	[66]	It helps museum curators improve cultural metadata quality and information retrieval by automating artwork annotation, refining search results, and using semantic reasoning with ML for more accurate predictions.	Cultural/economic sustainability	Collection management	Automated Cataloging; Curatorial Enhancement; Search Optimization; Knowledge discovery	ML; Semantic Reasoning; Semantic Search; Automation	Challenges include ensuring annotation accuracy and efficiency, limitations of iconographic thesauruses for diverse artworks, difficulties in applying ML algorithms to art collections, and complexities in integrating semantic and visual data.	Technical/ Operational Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
23	[47]	AI-generated "probability maps" improve art authentication by detecting forgeries and attributing works accurately, using CNN technology for precise visual pattern and brushstroke analysis, enhancing scholarly understanding.	Cultural/economic sustainability	Operational Efficiency	Art Authentication; Research Enhancement	CNNs; AI-generated probability maps, Visual Pattern Analysis/Visual Data Mining	There is a need to combine AI methods with traditional scientific analysis and human expertise, requiring careful and often complex integration.	Technical/ Operational Risks
24	[78]	In art, AI creates dynamic, data-driven works that explore new perceptions and abstractions, creating novel forms and visuals that push traditional boundaries.	Cultural sustainability	Collection management	Artistic Exploration; Immersive Experiences	GenAI; Data Driven Creation		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
25	[59]	AI (ML) systems enable art museums to uncover patterns in cultural data through methods like "distant seeing," optimize archival resource use, and promote public education and AI literacy by serving as testbeds for diverse audiences.	Cultural/social sustainability	Collection management	Archival Resource Management; Public Educational Literacy	ML; "Distant Seeing"	Challenges include labor exploitation, environmental harm, limited public involvement, and the overwhelming complexity of AI that discourages critical understanding and engagement.	Ethical/ Socioeconomic Risks; Environmental Risks; Social Risks
26	[14]	AI interactive systems, powered by database management, enhance in-depth exhibition design, offer diverse personalized experiences, boost visitor satisfaction, optimize museum management (visitor flow, resource use), and promote cultural value transmission.	Economic/social/ cultural sustainability	Operational Efficiency; Visitor Experience	Museum/ Operation Management; Exhibition Design; Experience Optimization; Cultural Value Transmission	Database management; AI interactive systems		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
27	[38,48]	AI aids in preserving aging and fading artworks, as demonstrated by the Rijksmuseum (e.g., *Operation Night Watch*) and the Van Gogh Museum.	Cultural economic sustainability	Operational Efficiency	Art Conservation	Neural Networks; Computational Restoration		
28	[55]	AI enhances collection access and discoverability, improves data handling efficiency, and fosters innovative learning and interaction methods.	Social/cultural sustainability	Collection management	Content Management;	ML; Image Recognition; DL; Automated Tagging	AI faces critical concerns including reinforcement of power structures like Eurocentrism and bias, unchecked tech solutionism, knowledge concentration, environmental impacts, and a need for transparency due to hidden labor, biased data, and poor documentation.	Ethical/ Socioeconomic Risks; Environmental Risks; Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
29	[131]	AI boosts knowledge discovery by uncovering complex patterns, fuels innovation with advanced data processing, and enriches cultural engagement through new ways to explore archives and art.	Cultural sustainability	Collection Management	Knowledge discovery; Innovation; Research; Cultural Engagement & Exploration	Advanced data processing; Pattern Recognition	Environmental impact covers energy use, carbon footprint, resource extraction, and exploitation. AI embeds biases and ethical concerns reflecting its creators' values. There's also a risk of tech solutionism and power concentration (e.g., Silicon Valley), highlighting the need for equity and decolonization.	Environmental Risks; Ethical/ Socioeconomic Risks
30	[115]	AI enriches visitor experience by sparking creativity, enabling human-AI co-creation, and encouraging public dialogue.	Social/cultural sustainability	Visitor Experience	Experience Enrichment; Co-creation; Public Dialogue Encouragement	GenAI	Ethical issues include training data concerns, missing artist consent and compensation, loss of curatorial control, and GenAI "hallucinations."	Technical Risks; Ethical/Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
31	[35]	AI improves visitor services, education and outreach, enhances museum experiences, optimizes management and workflows, boosts collection care, and advances research and analysis.	Cultural/social/ economic sustainability	Operational Efficiency; Collection Management; Visitor Experience	Operations Management; (Management and Workflow Optimization) Research; Education; Outreach; Visitor Service;	AI systems; AI-powered chatbots;	Unaddressed biases reinforce structural racism, colonialism, and gender inequality; AI-powered chatbots and robots risk replacing curatorial and service staff; and unequal global development leads to dominance by select countries and companies.	Ethical/ Socioeconomic Risks
32	[15]	AI helps museums strengthen visitor relationships by personalizing experiences, aiding navigation, and providing real-time answers to art-related questions.	Social/cultural/ economic sustainability	Visitor Experience	Experience Personalization; Navigation Assistance; Real-time information Provision; Visitor Relationship Strengthening		Underuse of interactive AI leads to one-way social media communication and low user engagement, limiting meaningful visitor interactions.	Implementation/ Operational Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
33	[67]	At Nasjonalmuseet, AI boosts digitization, accessibility, and relevance through semantic search, contextual understanding, advanced image analysis, feedback-driven refinement, and open-source AI.	Cultural/social/ economic sustainability	Collection management	Knowledge Discovery; Accessibility Enhancement; Educational Engagement	Semantic Search; Image Analysis	Challenges include content sensitivity, multilingual ambiguities, slow performance, and reliance on commercial AI models misaligned with CH needs.	Technical/ Operational Risks; Governance/ Socioeconomic Risks
34	[45]	AI tools are reshaping fine arts by enabling rapid creation, analysis, classification and transformation of artworks.	Cultural/social/ economic sustainability	Operational Efficiency; Collection Management; Visitor Experience	Collection Enhancement; Co-Creation; Art Authentication	GenAI	The use of AI in art raises significant challenges concerning authorship, copyright, and the nature of human creativity.	Ethical/ Philosophical Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
35	[20]	AI enhances museum experiences through customization, interactive content, real-time insights, and immersive engagement, while also improving data analytics, digital preservation, security, artwork authentication, curatorial decision-making, conservation tracking, and visitor behavior analysis.	Cultural/social/ economic sustainability	Operational Efficiency; Visitor Experience	Digital Preservation; Security Management; Conservation; Curatorial Enhancement; Art Authentication; Audience Engagement; Experience Optimization		AI implementation faces challenges like interpretation difficulties, lack of expertise, restricted data access (due to privacy, security, and quality), high infrastructure costs, privacy concerns, and ethical issues like bias, transparency, and consent.	Technical/ Operational Risks; Ethical/ Governance Risks
36	[8]	AI-driven personalization enhances visitor engagement and satisfaction, improves brand perception of heritage sites, supports CH preservation, and increases visitor duration.	Cultural/economic sustainability	Operational Efficiency; Visitor Experience	Museum Branding and Marketing; CH Preservation; Visitor Engagement and Satisfaction	AI-driven Personalization	Data privacy and security concerns.	Ethical/Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
37	[25]	AI empowers museums to integrate into digital knowledge cultures, create immersive hybrid experiences, enhance education for critical engagement with AI tools, and advance collection analysis through sophisticated image and context recognition—strengthening their cultural and educational mission.	Cultural/social/ economic sustainability	Collection management; Visitor Experience	Digital Curation; Education and Critical AI Literacy; Experience Optimization	Image and Context Recognition;	Ethical concerns (privacy, bias, data accuracy, agency, inclusion), misalignment of AI pace with museum workflows, skepticism and hesitation, loss of contextual data in ML preparation, "hallucinations", and the need to adapt education and publications for AI tools.	Ethical Risks; Technical/Operational Risks; Socioeconomic/ Cultural Risks
38	[80]	AI enhances visitor engagement through chatbots and robot critics, automates content creation and recommendations, supports research and analytics for collections, and enables creative content like text-to-image and voice generation.	Cultural/social sustainability	Visitor Experience; Collection management	Visitor Engagement; Research; Co-creation	Chatbots and Robot critics; Recommendation Automation; Text-to-image and voice generation tools.	AI adoption in museums faces resource constraints, algorithmic errors, ownership and copyright issues of AI-generated content, bias amplification, oversimplification, minority erasure, AI "hallucinations", risks to vulnerable groups (e.g., via geolocation, FRT), and uncertain long-term impacts.	Technical/ Operational Risks; Socioeconomic Risks; Ethical/ Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
39	[37]	AI optimizes operations and strategy by analyzing visitor behavior, refining exhibition design, managing crowds, allocating resources, and forecasting attendance. It enhances visitor engagement with personalized recommendations and virtual assistants, advances heritage preservation via digitization and reconstruction, expands audience reach by promoting inclusivity and global collaboration, and sustains relevance by driving innovation and addressing public needs.	Cultural/social/ economic sustainability	Operational Efficiency; Visitor Experience	Strategic Planning; Visitor Management; Resource Allocation; Conservation; Digital Preservation; Visitor Assistance; Audience Engagement and Personalization; Inclusivity	Visitor Behavior Analysis; Recommendation Systems; Virtual Assistants; Predictive Analytics	Ethical concerns include data privacy, algorithmic bias, and accessibility; integration challenges involve technical barriers, high costs, and the need for skilled staff.	Technical/ Operational Risks; Ethical/ Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
40	[52]	AI automates metadata tagging, enhances search and discovery, and offers personalized recommendations. It improves accessibility for people with disabilities, supports mindfulness to reduce stress, and fosters engagement by enabling visitor interaction and contribution to exhibits.	Cultural/social sustainability	Collection management; Visitor Experience	Content Management; Knowledge Discovery; Visitor Engagement and Personalization; Accessibility and Inclusion; Wellbeing and Mindfulness Support	Automated Metadata Tagging; Recommendation Systems; Accessibility Tools (e.g., NLP, CV)	Challenges include reliability, biased outputs, privacy concerns, ethical use, need for skilled human oversight, resource demands for AI training, scarce in-house expertise, and high implementation costs.	Technical/ Operational Risks; Ethical/ Governance Risks
41	[3]	AI transforms collection management and experience design, personalizes visitor journeys, and preserves cultural treasures via advanced digitization. It boosts engagement, streamlines operations, promotes inclusivity, and reinforces museums' roles as stewards of knowledge, culture, and education.	Cultural/social sustainability	Operational Efficiency; Collection management; Visitor Experience	Museum Management; Digital Preservation; Visitor Engagement; Inclusivity; Knowledge and Cultural Stewardship	Advanced Digitalization; Personalization Systems; Interactive Engagement Tools	Ethical concerns include biases, transparency, accountability, and privacy, with implications for human rights, dignity, cultural values, and social responsibility. There are risks of reinforcing inequalities or distorting cultural representation, highlighting the need for robust ethical frameworks.	Ethical/Social Risks; Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
42	[126]	AI personalizes online experiences, boosts interactivity through gamification, AR/3D, and simulations, improves accessibility with image recognition and multilingual support, enhances artistic design, deepens educational storytelling, and drives data-informed curation.	Cultural/social sustainability	Visitor Experience	Experience Optimization; Digital Curation; Educational and Interpretive Storytelling; Artistic and Curatorial Support	AI personalization algorithms; Gamification; Image Recognition; Multilingual support systems	Data privacy concerns (e.g., GDPR compliance in the British Museum case), bias in narratives requiring adaptability, and ethical responsibility in AI deployment through strategic oversight.	Ethical/Social Risks; Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
43	[129]	AI transforms museum collection management and visitor experiences by enhancing accessibility and personalization, optimizing operations, preserving CH, ensuring ongoing relevance and innovation, and fostering critical public dialogue while enriching educational and cultural engagement.	Cultural/social/ economic sustainability	Operational Efficiency; Collection Management; Visitor Experience	Operations Optimization; CH Preservation; Accessibility and Personalization; Critical Public Dialogue; Educational and Cultural Engagement	ML; Data Analytics	Implementing AI in museums faces challenges including skepticism about its necessity and impact, operational and ethical issues such as bias, lack of transparency, overstimulation, inclusivity paradoxes, fear rooted in low AI literacy and concerns over replacing human expertise, and limited research on AI's actual benefits and risks, which may impede effective adoption and competitive advantage.	Ethical/Governance Risks; Social/Cultural Risks; Operational/ Strategic Risks
44	[17]	AI-powered Automatic Exhibition Guide Systems provide personalized audio-visual guides on mobile devices, boosting visitor engagement.	Cultural/social sustainability	Visitor Experience	Personalized guidance; Engagement	AI-powered guide systems; Mobile device integration	High costs and ongoing maintenance requirements.	Operational/ Strategic Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
45	[9]	Enhances digital storytelling and online visitor experiences, and supports collection management.	Cultural sustainability	Collection Management; Visitor Experience	Digital storytelling; Online Visitor Experiences;	AI-driven tools	Challenges include data privacy, algorithmic bias, historical data accuracy, reliance on funding and digitization policies, limited regional adoption, and the need for qualitative, longitudinal research.	Ethical/Governance Risks; Technical Risks; Operational/ Strategic Risks
46	[50,51, 53]	AI enables algorithmic curation and content generation. It produces original artworks and interactive experiences.	Cultural/social sustainability	Operational Efficiency	Algorithmic Curation; Content Generation	GenAI	AI-driven curation lacks distinct curatorial voice and risks undermining authenticity and creativity. Human expertise remains irreplaceable.	Ethical/ Philosophical Risks; Socioeconomic/ Cultural Risks
47	[68,69]	AI uncovers hidden connections in large visual archives, linking artworks across time, culture, and exhibitions for research and visitor engagement.	Cultural/social sustainability	Collection Management	Cross-collection Analysis	Pattern Recognition, CV, ML		

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
48	[74]	AI enables interactive co-creation by transforming artwork images into AI-generated versions from alt text, offering visitors playful engagement and critical reflection.	Cultural/social sustainability	Collection Management	Artistic Reinterpretation	GenAI		
49	[134]	AI enhances accessibility and inclusion, advances preservation, and supports creative production. Using ML, CV, and GenAI, it personalizes experiences, restores artifacts, and automates museum functions.	Cultural/social/ economic sustainability	Operational Efficiency; Collection Management; Visitor Experience	CH Preservation; Conservation; Accessibility; Inclusion; Creative production; Experience Personalization	ML; CV; GenAI	AI presents ethical and philosophical challenges to CH, including undermined authenticity, biased interpretation, and contested authorship. It also raises the risk that digitization could be used to justify physical destruction.	Ethical/ Philosophical Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
50	AI-powered Chatbots [84,85,87,88,90–92,95,97–99,109–114]	AI chatbots enhance visitor accessibility, engagement, and satisfaction through personalized, on-demand assistance. They offer real-time support for wayfinding, exhibitions, and services, integrate gamification, and provide deeper historical insights. Supporting educational goals, they blend learning with entertainment, while virtual conversations with historical figures create immersive, emotional, and cognitive experiences.	Cultural/social sustainability	Visitor Experience	Digital Storytelling; Education; Interactive On-site Guidance; Visitor Services; Audience Engagement	AI Chatbots; Conversational AI;	Concerns include understanding diverse queries, budget constraints, limited human-like comprehension and contextual sensitivity, lack of full accessibility in one-size-fits-all solutions, privacy issues, and AI output bias.	Technical Risks; Operational/Strategic Risks; Ethical/ Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
51	AI-based Recommendation & Personalization Systems [96,100–108]	AI enhances visitor experience through personalized, real-time recommendations and interactive tools. It also boosts digital retail, on-site engagement, and promotes serendipitous discovery by introducing users to new content and exhibits.	Economic/cultural/ social sustainability	Visitor Experience	Digital Retail; Navigation Assistance; Personalized Tours; Educational Storytelling; On-site Visitor Experience Enhancement	AI-driven recommendation systems; Anti-recommendation Systems, Data Analytics; User Profile	AI implementation faces challenges including high costs, reliability, transparency, data privacy, bias, cultural context understanding, art misinterpretation, and over-reliance on AI.	Operational/ Strategic Risks; Technical Risks; Ethical/Governance Risks

Table A1. *Cont.*

A/O	Source	AI Benefits in Museums	Sustainability Impact	Application Domain	Museum Operations/Functions Enhanced	AI Methods/ Techniques/Tools Used	AI Challenges in Museums	Risk Areas
52	AI-based Immersive & Interactive Experiences [109–114]	AI-powered interactive museum implementations enrich visitor experiences with dynamic, co-created content tailored to individual preferences, empowering visitors. They turn static exhibits into immersive, multisensory interactions that inspire creativity, motivate participation, and deepen emotional and cognitive engagement.	Cultural/social sustainability	Visitor Experience	Cultural Mediation; Co-creation; Visitor Engagement; Artistic Expression; Collection Exploration; Education; Immersive Storytelling;	GenAI; ML; CV; Avatars/Deepflakes; Text-to-image/voice; Image Recognition; Soundscapes	AI implementation faces challenges including high costs, reliability, transparency, data privacy, bias, cultural context understanding, art misinterpretation, and over-reliance on AI.	Operational/ Strategic Risks; Technical Risks; Ethical/Governance Risks
53	AI-based Accessibility & Inclusion Tools [115–124]	AI revolutionizes online museum experiences by enhancing educational outreach and making exhibits more engaging and accessible.	Cultural/social sustainability	Visitor Experience	Educational Outreach; Accessibility; Content Customiazation	Adaptive Interfaces; Multilingual Support; ML; Sensory Technologies (haptics)		

Table A2. AI-Enhanced Operational and Strategic Efficiency (Benefits).

No	Enhanced Museum Areas	Key Functions	References
1	Strategic, Administrative & Institutional Management	Strategic Planning	[12,34,36,37]
		Operations (e.g., workflow) Optimization	[3,14,34,35,40–42,125,129]
		Resource Management & Allocation	[32,36,37]
		Museum Marketing (Branding, Audience Development)	[8,32,36]
2	Visitor Management & Exhibition Development	Visitor Experience Optimization	[20,32,36,37,39]
		Exhibition Design	[14,37,40–42,49,125]
		Security & Safety Management	[20,34]
3	Scientific Research & Curatorial Innovation	Scientific Research	[35,43,44]
		Art Authentication	[20,45–47]
		AI-Assisted/Algorithmic Curation	[20,49–51,53]
		Knowledge Discovery	[49]
4	Collections Care & Preservation	Art Conservation	[20,37,38,48,129,130]
		Digital Preservation	[3,20,37]
		CH Preservation	[3,8,35,129,130]

Table A3. AI-driven Collection Management (Benefits).

No	Enhanced Museum Areas	Key Functions	References
1	Cataloging & Interpretation	Metadata Enhancement & Automated Cataloging	[32,52,54,55,64–66,80]
		Content Management & Interpretation	[59,63,70,131]
2	Collection Access & Navigation	Inclusive Digital Access & Collection Navigation	[3,64,65,67,130]
		Search & Information Retrieval Optimization	[52,54,55,63,66]
		Knowledge Discovery	[66,68–70,80,131]

Table A3. *Cont.*

No	Enhanced Museum Areas	Key Functions	References
3	Creative/Artistic & Conceptual Exploration	Creative Exploration	[45,72]
		Artistic Production	[76,78,130]
		Conceptual Exploration	[70]
4	Public Engagement & Cultural Stewardship	Innovative Public Education & Outreach	[25,35,55,59,64,68,69,72,129,131]
		Data Sharing	[65,67]
		Cultural Stewardship	[3,68,69,129]
		Co-creation	[65,74]

Table A4. AI-Powered Visitor Experience (Benefits).

No	Enhanced Museum Areas	Key Functions	References
1	AI-powered Chatbots & Virtual Assistants	Visitor Assistance & Navigation	[15,80,83–85,96,97]
		Real-time Information Provision	[15,20,34,86,89–91]
		Visitor Relationship Strengthening	[15,98,99]
2	AI-based Recommendation & Personalization Systems	Personalized Experiences & Tours	[3,17,83–85,96,103,104,106–108]
		Content Recommendation & Customization	[8,20,49,52,80,103–105,129]
		Digital Retail & E-commerce Guidance	[100–102]
3	AI-driven Immersive & Interactive Experiences	Interactive & Immersive Learning	[13,14,20,25,113,114,123,124]
		Interactive Engagement & Co-creation	[52,80,81,83,109,115,116,122,125,126,130]
		Digital Storytelling & On-site Experiences	[9,34,126]
4	AI-enhanced Accessibility & Inclusion Tools	Accessibility & Inclusion Support	[3,37,52,125–128,130]
		Wellbeing & Mindfulness Assistance	[52]
		Educational & Cultural Engagement	[35,120,129]
		Critical AI Literacy & Public Dialogue	[25,83,115,129]

Table A5. AI-Enhanced Operational and Strategic Efficiency, Collection Management and Visitor Experience (Challenges/Risks).

No	Challenges/Risks	Risk Areas	References
1	Technical & Operational Risks	Technical limits: accuracy, reliability, cultural/contextual gaps, misclassification, oversimplification, GenAI hallucinations	[25,34,37,40–44,49,52,65,66,70,76,80,92,125]
		Data integrity issues: limited/biased datasets, ambiguity, content sensitivity, art interpretation subjectivity	[9,12,20,25,34,36,37,52,54,55,65–67]
		High infrastructure and maintenance costs; resource constraints, training complexity, scarcity of skilled staff, staff mindset & skill gaps	[17,20,32,34,37,52,80]
2	Ethical, Philosophical & Governance Risks	Data privacy & security concerns (GDPR compliance, geolocation risks, FRT misuse). Risks for vulnerable groups.	[3,8,9,20,37]
		Bias amplification (e.g., racism, colonialism, gender inequality) & discrimination, offensive outcomes, narrative distortion	[3,9,25,35,37,52,55,63,80,126]
		Transparency, consent & compensation issues, accountability, oversight loss, human rights misalignment, brandwashing, weak regulation, curatorial voice and creativity risks.	[3,9,20,25,36,45,50–53,55,76,80,115,126,130]
3	Socioeconomic & Cultural Risks	Funding dependency. Tension between commercial goals and scholarship.	[9,36,67]
		Labor exploitation, hidden/underpaid work. Power imbalances, minority erasure, unequal global AI dominance.	[35,55,59,80,130]
		Limited public involvement, discouraging complexity.	[59]
		Human Workforce Impact: staff replacement risk, AI over-reliance, sceptisism, fear/resistance.	[35,80,129,130]
		Underuse of interactive AI leading to low engagement and one-way communication	[15]
4	Environmental Risks	Environmental impacts: energy use, carbon footprint, resource extraction.	[55,59]

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