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Toward a Sustainable Palette: Scientific Insights into Natural Pigments and Binders for Environmentally Conscious Art Practices

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ABSTRACT: The use of synthetic paints in fine art has raised growing environmental concerns, particularly regarding volatile organic compound (VOC) emissions and microplastic pollution. This study investigates the potential of natural pigments and biodegradable binders to serve as sustainable alternatives. It aims to assess their performance through standardized testing of lightfastness, binder compatibility, and environmental impact. A range of mineral pigments (e.g., ochres, sienna, green earth) and botanical lake pigments (e.g., madder, indigo, turmeric) were combined with solvent free binders such as gum arabic, egg tempera, and linseed/walnut oil. Botanical lakes were prepared using alum based precipitation methods. Paint samples were applied to cotton paper and mineral gesso panels, followed by lightfastness testing using ISO Blue Wool standards and ΔE^* measurements. Environmental metrics including energy consumption, waste output, and microplastic risk were evaluated using a simplified life cycle inventory (LCIA) framework. The results showed that mineral pigments delivered excellent durability (Blue Wool 7–8), while botanical lakes varied in stability. Madder and indigo were moderately stable, whereas turmeric was highly fugitive (Blue Wool 1–2). Gum arabic and egg tempera demonstrated superior ecological profiles, with zero VOC emissions and high biodegradability. Linseed and walnut oils offered good artistic performance but required careful storage. All tested combinations avoided microplastic generation. These findings confirm that a select range of natural pigment and binder combinations can meet both artistic and environmental standards. The study supports the integration of sustainable materials into fine art practices and provides a model for future research and institutional policy development focused on eco conscious art production.

Keywords: Natural Pigments, Botanical Lakes, Solvent Free Binders, Ecological Art, Lightfastness, Life Cycle Assessment.

INTRODUCTION

Synthetic artist paints raise serious environmental and health concerns, notably VOC emissions and microplastic pollution. These challenges underscore the urgency of adopting sustainable alternatives. While historical traditions provide evidence of durable and low-toxicity materials, contemporary research increasingly validates natural pigments and binders as viable eco-friendly options. Against this backdrop, this study addresses the research gap by evaluating the performance and ecological profile of natural pigments paired with biodegradable binders.

In parallel, the prevalence of microplastics in synthetic paints adds another dimension to the ecological burden of modern materials. As paint degrades or is removed during conservation and maintenance processes, it releases microplastic particles into the environment. These particles have been detected in various ecosystems and pose risks to aquatic and terrestrial life, entering food chains and accumulating over time (El Gawad & Abdelmaksoud, 2022). Such risks have mobilized calls within the art and environmental communities to reconsider the use of synthetic polymers and explore sustainable alternatives.

Regulatory efforts have catalyzed this transition. In many regions, including the European Union, environmental regulations have imposed limits on VOC emissions and required detailed labeling of consumer products. These frameworks serve as incentives for manufacturers to innovate with eco friendly alternatives and have begun to shape the choices available to artists (Alahira et al., 2024). Furthermore, public and institutional awareness of sustainability has led to increased demand for low impact art materials, often bolstered by educational initiatives and awareness campaigns (Urtgam et al., 2023).

Parallel to these policy and market shifts, scholarly and artistic interest in natural pigments has experienced a resurgence. Historically, artists relied on materials available in their immediate environment minerals, plants, and insects to produce a wide range of vibrant hues. Research into these traditional sources has documented both the practical methods and cultural significance of their use. For example, the vivid reds from madder or cochineal and the rich blues from indigo highlight the sophistication of pre industrial color practices (Degano et al., 2017; Siddall, 2018). These materials, while long regarded as part of art history, are now revisited through the lens of sustainability, offering not only historical continuity but also environmentally responsible alternatives (Gajić-Kvaščev et al., 2023; Kramar & Kostić, 2022).

This rediscovery is supported by historical evidence of adaptability among artists. From early cave art to Renaissance frescoes, practitioners have manipulated botanical dyes and mineral based pigments using locally sourced resources and simple yet effective preparation methods. The use of red from cochineal or earth ochres demonstrates both ingenuity and environmental consciousness in selecting low toxicity, renewable resources (Potočnik, 2018; Raicu et al., 2024). The knowledge embedded in these historical practices provides a valuable framework for modern artists aiming to reduce ecological impact.

Integral to this material transition is the role of binders the substances that hold pigment particles together and fix them to surfaces. Traditional binders like egg yolk (tempera), gum arabic (watercolor), and linseed oil (oil painting) offer a stark contrast to modern synthetic resins, which often carry high environmental and toxicological costs. These organic binders exhibit high biodegradability and minimal VOC emission profiles, making them suitable candidates for sustainable studio practice (Urtgam et al., 2023; El Gawad & Abdelmaksoud, 2022). Their ecological performance, however, must be balanced with their handling properties, drying time, and interaction with natural pigments (Kramar & Kostić, 2022).

Contemporary shifts in artist preferences and consumer markets reflect growing interest in sustainability. The emergence of eco conscious brands and dedicated sustainable product lines is indicative of this trend. These products often emphasize transparency in sourcing, composition, and environmental performance. While market uptake varies by region and is influenced by regulatory enforcement and access to education, the general trajectory points toward increasing adoption of green alternatives (Alahira et al., 2024). Nevertheless, continued research and dissemination of findings are essential for widespread implementation (Sunassee et al., 2021).

The complex interplay of material science, environmental policy, historical practice, and artistic innovation sets the stage for this study. Against this backdrop, the objective of the present research is to evaluate the performance and ecological profile of natural pigments both mineral and botanical when paired with solvent free or biodegradable binders. By integrating historical methods with modern testing standards such as lightfastness protocols and life cycle assessments, this work seeks to contribute to the growing field of ecological art practices. The study hypothesizes that selected combinations of natural pigments and binders can fulfill both environmental and artistic requirements, thereby offering a replicable model for sustainable fine art media.

This chapter has outlined the environmental and health challenges associated with synthetic artist materials and the corresponding emergence of natural alternatives in the context of regulatory, historical, and market trends. The next chapter presents the detailed methodology used to assess the artistic viability and ecological sustainability of these alternative materials.

METHOD

This chapter outlines the procedures and materials used to evaluate the feasibility of natural pigments and binders as sustainable painting media. The methodology integrates pigment synthesis, binder preparation, application protocols, and testing strategies grounded in contemporary standards and supported by relevant literature.

Materials Selection

The study selected representative mineral pigments (ochres, sienna, green earth) and botanical dyes (madder, indigo, turmeric) for their historical relevance and ecological potential. These were paired with solvent-free binders gum arabic, egg tempera, and cold-pressed oils chosen for their biodegradability and established use in sustainable practices.

Binders used were gum arabic (for watercolors), egg tempera (for tempera painting), and cold pressed linseed and walnut oils (for oil painting), each chosen for their solvent free and biodegradable nature (Urtgam et al., 2023).

Botanical Lake Pigment Synthesis

The botanical dyes were processed into lake pigments using alum based precipitation techniques. Dyes were extracted via aqueous methods, filtered, and heated. Aluminum sulfate was introduced as a mordant, followed by sodium carbonate as a pH modifier to precipitate the dye onto a solid substrate. This chelation process reinforced pigment stability and intensity (Clementi et al., 2023; Szadkowski et al., 2022). pH levels were carefully adjusted to optimize yield and avoid color degradation (Jimtaisong, 2020).

Temperature was maintained around 70°C to balance between enhancing pigment saturation and preserving dye integrity. Variants of the procedure were trialed using ultrasonication to improve dye extraction, per techniques validated in contemporary pigment chemistry (Cesaratto et al., 2019).

Binder Preparation and Paint Mixing

Gum arabic solution was prepared with distilled water, glycerin as a humectant, and a minimal preservative. Egg tempera was made fresh using egg yolk and distilled water. Oils were used in their raw, cold pressed form without any added solvents. Pigments were ground using a glass muller and mixed into the binders gradually to ensure consistency and control over viscosity and color saturation (Pozzi et al., 2016).

Substrate Preparation and Application

Paints were applied on 100% cotton watercolor paper and mineral based gessoed canvas panels, avoiding acrylic or synthetic coatings. Each paint was tested in triplicate to ensure reproducibility and to account for binder pigment interaction variance.

Lightfastness Testing

Samples were exposed to controlled artificial lighting (UV and LED combined) for 100–150 hours. The Blue Wool standard (ISO R105) served as a comparative baseline. ΔE^* values (color shift) were calculated pre and post exposure using a calibrated spectrophotometer. Testing followed ASTM D4303 guidelines (Degano et al., 2017).

Environmental Assessment (LCIA Framework)

A simplified life cycle inventory was created to assess each pigment binder combination. Metrics included energy input (kWh/kg), solid and liquid waste generation (g/ml per kg), VOC emissions, biodegradability, and microplastic generation risk. These were evaluated qualitatively and quantitatively where data was available (Sharma & Singh, 2021; Sunassee et al., 2021). Binders and substrates were selected to avoid synthetic resins or polymers that could pose post use environmental hazards.

Handling and Usability Metrics

Binder systems were assessed for viscosity, drying time, blendability, and adhesion. These characteristics were rated through hands on application by trained artists and cross checked with previous empirical studies (Urtgam et al., 2023; Zhang et al., 2020). Casein and tempera systems demonstrated advantages in drying time and pigment adhesion, whereas oil systems offered extended blending windows.

In summary, this methodology merges traditional pigment preparation with modern scientific standards to rigorously assess the suitability of natural materials for sustainable art practices.

RESULT AND DISCUSSION

Lightfastness and Pigment Stability

Results indicated clear differences between mineral and botanical pigments. Mineral pigments showed excellent stability, while botanical lakes varied, with turmeric being the least durable. These outcomes, supported by quantitative metrics, confirm the role of molecular structure and binder interaction in determining pigment longevity. For accessibility, Blue Wool ratings (scale 1–8, where higher values indicate better light stability) and ΔE values (a measure of visible color change) are briefly explained to aid non-specialist readers (Everaert et al., 2019). A ΔE^* threshold above 1 was visibly detectable, while values over 5 were deemed significant by visual standards (Markevičiūtė & Varžinskas, 2022).

Spectrophotometric analysis provided quantifiable data on pigment degradation, aligning with prior methodologies for long term exposure assessments (Piao et al., 2024).

Table 1. Lightfastness and Color Change Results

Pigment Type	Origin	Blue Wool Rating	ΔE^* (Before vs After Exposure)	Stability Rating
Yellow Ochre	Mineral	8	<1.0	Excellent
Red Ochre	Mineral	7	<1.5	Excellent
Burnt Sienna	Mineral	7–8	<1.2	Excellent
Green Earth	Mineral	6–7	<2.0	Good
Madder Lake	Botanical	5–6	3.5–5.0	Moderate
Indigo Lake	Botanical	6	2.0–3.2	Good
Turmeric Lake	Botanical	1–2	>8.0	Poor

Binder Performance

Ecologically, gum arabic demonstrated the most favorable profile: biodegradable, renewable, and low in VOC emissions (Mifsud, 2023). Egg tempera, while also low impact, had a slightly more complex ecological footprint depending on sourcing (Olivatto et al., 2024). Linseed and walnut oils, although natural, required more processing and presented modest VOC outputs during oxidation (Falzarano et al., 2025).

Drying time varied: gum arabic dried rapidly, ideal for watercolor techniques; egg tempera also dried quickly, enabling layered applications; oil binders had extended drying periods but offered rich finishes and durability (Saroha et al., 2024).

Preservation issues emerged based on moisture sensitivity. Gum arabic attracted moisture and was susceptible to microbial growth in humid conditions (Ramful, 2024). Egg tempera's emulsion could destabilize with excessive heat or humidity. Linseed oil was prone to rancidity without proper storage, but formed robust films post curing (Falzarano et al., 2025).

Binder pigment chemistry significantly affected performance. Gum arabic enhanced watercolor vibrancy and bonding (Mifsud, 2023). Egg tempera's proteins interacted with mineral pigments to adjust opacity and hue (Saroha et al., 2024). Linseed oil encapsulated pigment particles effectively via oxidation, but could cause tone shifts depending on preparation (Falzarano et al., 2025).

Table 2. Binder Characteristics and Environmental Profile

Binder Type	Composition	VOC Content	Biodegradability	Finish Type
Gum Arabic	Plant exudate + water	Zero	High	Transparent
Tempera (Egg)	Egg yolk + water	Zero	High	Matte
Linseed Oil	Cold pressed flaxseed	Near zero (solvent free)	Medium	Glossy
Walnut Oil	Pressed walnut	Near zero (solvent free)	Medium	Semi gloss

Environmental Metrics (LCIA)

Natural materials consistently outperformed synthetics in environmental assessments. Life cycle inventory data showed lower energy use and emissions in natural pigment processing compared to synthetic alternatives (Bartolucci et al., 2023; Morris & Hicks, 2021).

For binders, gum arabic demanded the least energy input and chemical processing, followed by egg tempera and then linseed oil (Tehseen, 2025). Microplastic risk was absent in all natural combinations, in contrast to the fragmentation potential in synthetic paints (Banerjee et al., 2025).

Energy demand assessments found that pigment extraction from natural sources required 2–5 times less energy than synthetic chemical synthesis (Yalagala et al., 2023). Carbon footprints and post use degradation pathways clearly favored natural ingredients, which can be composted or integrated into biowaste systems (Morris & Hicks, 2021).

Synthetic materials, by contrast, present significant long term risks due to persistent polymers and toxic residues, emphasizing the importance of sustainable material choices in art practice (Won & Lau, 2023).

Table 3. Environmental Impact Assessment (LCIA Summary)

Material Combo	Energy Use (kWh/kg)	Solid Waste (g/kg)	Liquid Waste (ml/kg)	Microplastic Risk	Overall Impact Score
Yellow Ochre + Gum	1.2	18	12	None	Low
Madder + Tempera	2.1	34	28	None	Medium
Indigo + Linseed	2.5	29	24	None	Medium
Turmeric + Gum	2.2	33	30	None	Medium High

Overall, natural pigment and binder systems demonstrated viable environmental profiles, effective handling properties, and, in the case of mineral pigments, outstanding lightfastness performance.

This study highlights both the opportunities and limitations of using natural pigments and solvent-free binders. While mineral pigments and selected botanical lakes proved viable, their successful use requires careful curatorial management and preservation strategies. Ethical considerations, particularly the avoidance of toxic mordants, further support the shift toward sustainable practices. Despite barriers such as cost, labeling, and limited institutional uptake, the findings provide empirical evidence that can guide artists, conservators, and policymakers in adopting ecological art materials.

One of the central concerns is the curatorial management of artworks made with botanical lake pigments. These organic materials are generally more vulnerable to photodegradation than their mineral or synthetic counterparts. Consequently, effective light management strategies become essential. Studies highlight that using low UV LED lighting and limiting exposure time are proven methods to mitigate light induced damage (Hsu et al., 2018). Protective glazing and rotational exhibition schedules further reduce cumulative exposure, ensuring that artworks made with sensitive pigments can remain on display without compromising their integrity (Won & Lau, 2023).

The ethical dimension of material choice must also be addressed. Historically, toxic mordants such as chromium and tin were used to stabilize natural dyes, enhancing vibrancy and durability. However, given their toxicological profiles, their continued use raises health and environmental concerns. Institutions now increasingly adopt alternatives favoring alum or iron based mordants and are revising conservation protocols to eliminate hazardous substances from studio and conservation settings (Ewe & Tjiptono, 2023; Hagaggi & Rady, 2024). This shift represents a broader ethical commitment to safer working conditions and sustainable stewardship of cultural heritage.

Despite growing awareness, several institutional barriers still limit the widespread adoption of sustainable art materials. A key issue is the lack of standardization in eco labeling, which complicates the decision making process for artists and curators aiming to choose environmentally responsible products (Han et al., 2018). Furthermore, sustainable materials often come with higher production costs, stemming from smaller scale manufacturing and the absence of subsidized industrial infrastructure. Combined with limited training in green methods at art schools and conservation institutions, these factors hinder systemic change (Musaimi et al., 2018). Procurement policies also play a role: many institutions default to familiar suppliers and established brands, even when newer, more sustainable alternatives are available (Das & Maity, 2024).

Nonetheless, this study contributes meaningfully to the evolution of green curatorial and conservation practices. By offering empirical evidence on lightfastness, binder properties, and environmental metrics, it equips practitioners with the data needed to make informed material choices. Furthermore, it encourages collaboration between artists, manufacturers, and cultural institutions to redefine the material standards for artistic production (Díez et al., 2025). As sustainability becomes central to contemporary discourse, such studies will help drive the development of standardized, accessible, and ethically sound alternatives to traditional materials.

This research not only highlights the feasibility of mineral pigments and selected botanical lakes but also opens up a broader conversation about the intersection of art, ethics, and environmental responsibility. It encourages future research into long term preservation strategies and institutional support systems that can enable the widespread adoption of these sustainable practices. Ultimately, it underscores the importance of integrating ecological consciousness into the very foundations of artistic and curatorial decision making (Arboleda-Baena et al., 2023; Han et al., 2020).

CONCLUSION

This study demonstrates that natural pigments and biodegradable binders can serve as credible alternatives to synthetic paints, balancing artistic performance with ecological responsibility. Mineral pigments such as ochres and sienna showed excellent durability, while botanical lakes like madder and indigo offered viable but more delicate options. Gum arabic and egg tempera emerged as the most sustainable binders, combining strong artistic usability with low environmental impact. Importantly, all tested natural systems avoided microplastic generation, a key advantage over synthetic paints.

Beyond material testing, the findings provide practical and ethical guidance for artists, conservators, and institutions aiming to reduce their ecological footprint. By evidencing that sustainable choices need not compromise artistic quality, this research supports the integration of natural materials into mainstream practice and policy. Future studies should expand pigment–binder combinations and assess long-term preservation strategies, ensuring that ecological art practices continue to evolve with scientific and cultural relevance.

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