Purified Linseed Oil: Considerations for Use on Historic Wood

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Linseed oil is enjoying a well-deserved renaissance as a wood finish for preservation projects, but its success depends on multiple factors.

Fig. 1. The historic White Grass Ranch in Grand Teton National Park, Wyoming, built 1913, is comprised of 14 buildings that retain a high degree of original wood. Linseed-oil paint systems have been used to protect exterior wood elements, which are regularly exposed to summertime 50-degree temperature swings, high elevation, ultraviolet radiation, and an average of 200 inches of winter snowfall, 2020. All images courtesy of the U.S. National Park Service.

By synthesizing existing information and research, this article aims to provide a useful examination of the advantages and disadvantages of using modern purified linseed-oil systems on historic wood exteriors. Geared toward professionals unfamiliar with this treatment, the article discusses the characteristics and performance of purified linseed-oil paint and lists important considerations to evaluate before using it in any project.

Linseed oil from pressed flax seeds has been used in the Middle East and Europe in artists' paints and resins since the twelfth century and in architectural paints since the seventeenth century.[1] In the United States, linseed oil was the dominant vehicle and binder used in exterior paints starting in the late eighteenth century and ending in the 1950s (Fig. 1).[2] Historically, linseed-oil paints commonly had lead white, turpentine, Japan drier, and/or cobalt or manganese driers added to them, in addition to the earth pigments that gave the paint its color and opacity.[3] These additives modified the paint's flow, durability, drying time, and resistance to biological attack.

Linseed-oil paints were eventually supplanted by synthetic paints that offered and marketed convenience; they did not require a skilled painter and dried in a matter of hours, rather than days. This change was first seen in the 1930s with the advent of faster-drying alkyd oil paints, although those paints still contained up to 60 percent of linseed oil by weight. By the end of the 1950s, synthetic resins became widespread and eventually pushed linseed-oil paints out of the market.[4] The rapidity and completeness with which synthetic paints overtook the market is exceptional. Consider that in the span of 60 years, linseed-oil paint, the dominant paint in the U.S. for 200 years, has almost completely faded from consumer consciousness.

Qualities of Linseed Oil

High-quality linseed oils have been cold-pressed and cleaned of mucilage and proteins, leaving an oil comprised of only unsaturated fatty acids and glycerol.[5] As a "drying oil," its molecules polymerize by bonding to one another in the presence of heat and/or oxygen, resulting in a solid, flexible film.[6] Removing proteins and organic matter from the oil eliminates readily available food sources for microorganisms.[7] Today, the terms "purified" or "degummed" linseed oil denote a cold-pressed oil that is free from mucilage and protein, as well as free from additives like biocides, solvents, or toxic driers.

Due to economies of scale, linseed oil available in hardware and home-improvement stores generally has not been cold-pressed or cleaned of proteins and can include toxic biocides, solvents, and/or driers. If additives are used, they serve to reduce drying time, increase shelf life (oil containing proteins can spoil), change the oil's consistency, and/or inhibit mildew growth. Mildew can grow easily on unpurified linseed oil, even those with an added mildewcide, since proteins that act as a food source remain within the oil after the mildewcide ages and loses its effectiveness.[8]

Purified, or degummed, linseed oil is broadly categorized into two types: raw or boiled. However, there are variations even within these distinctions, and these terms may have different definitions depending on the manufacturer or geographic location. In general, purified raw linseed oil is cold-pressed oil that has been cleaned of mucilage and proteins but thereafter is only minimally exposed to heat.[9] It has a small molecular structure and low viscosity, which cause it to penetrate deeply into wood, fill the structure with oil, and create a hydrophobic environment.[10] Raw linseed oil is meant to be absorbed rather than sit on the surface and form a film, as it has a very long dry time. It is commonly used as a protective treatment and is applied either to weathered wood, exposed wood that is not meant to be painted, or as a primer prior to painting.[11]

Purified boiled linseed oil is degummed oil that has been heated to approximately 250°F to 400°F over a couple hours to a couple days depending on the manufacturer.[12] Exposure to heat starts the initial polymerization of the oil, during which oil molecules cross-link with each other and form macromolecules. Partial polymerization results in two characteristics that explain why boiled linseed oil is used to make linseed-oil paint. First, it increases the oil's viscosity so that it is absorbed shallowly into the wood, leaving oil on the surface to form a film. Second, it shortens the oil's dry time to about 24 to 48 hours. Pigments added to the boiled linseed oil remain bound in the oil on the wood surface and give the paint its color and opacity (Fig. 2).[13]

Purified linseed-oil paints use zinc oxide, an established fungicide and alternative to lead, to inhibit mildew growth, especially on wet paint films.[14] Some have zinc oxide already incorporated in their formulations, while others require the painter to add it separately prior to application.

It is less common for manufacturers to add a fungicide to purified raw linseed oil, as it does not form a surface film that holds water considered necessary for mildew growth. In contrast, the hydrophobic environment created within the wood by the raw oil is the reason that it is commonly used to control fungi and other decay organisms in wood.[15] This is not to say that purified raw linseed oil cannot mildew under the right conditions, only that the risk is low enough to negate the need for an added fungicide.

Characteristics of Modern Coatings

Many U.S. National Park Service (NPS) historic buildings painted with waterborne latex and acrylic paints often experience blistering, peeling, and cracking, frequently sooner than the five to eight years considered normal for their service life. For buildings with regular maintenance cycles, repainting results in an overall increased paint-film thickness. In some cases, years of repeated painting have masked serious wood decay: There are examples of layers of built-up latex paint encapsulating hollowed-out wood members that remained held together by only the paint film (Fig. 3). For buildings without frequent painting maintenance that remain in a cracked or peeled condition, rot is also observed. In short, both intact, thick, modern paint films and

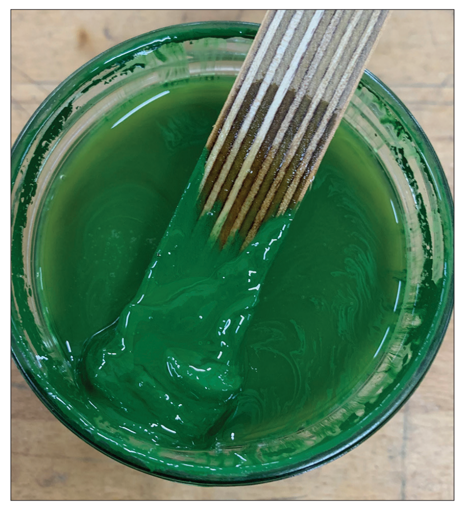


Fig. 2. Linseed-oil paint is made of purified boiled linseed oil and earth pigments, which settle to the bottom as a mass over time and require stirring to evenly disperse the pigment into the paint. Linseed-oil paints also contain traces of manganese to shorten drying time and in some cases, less than 3 percent paraffin to add flexibility, 2020.

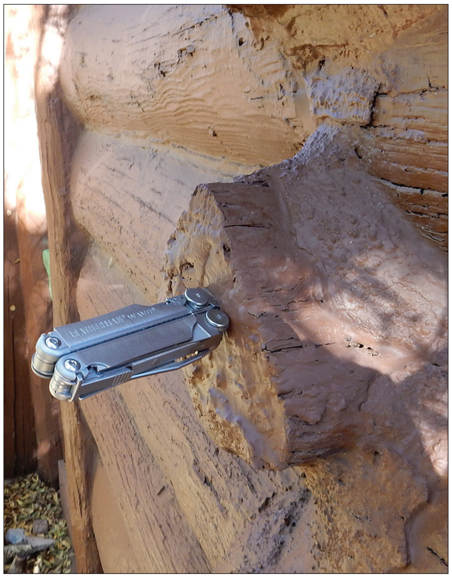


Fig. 3. Only a shell of waterborne paint is holding these decayed, hollowed-out log crowns together after decades of repainting with new waterborne latex and acrylic paint. Regular repainting without examining the condition of the underlying wood resulted in built-up paint layers that hid the wood decay, 2016.

deteriorated, thin, modern paint films are correlated with rot.

These patterns of deterioration are consistent with prolonged contact or trapped moisture in the wood substrate, either from liquid water entering from the exterior or from water vapor migrating out from the interior. The following generalized characteristics of waterborne coatings commonly used on NPS wood buildings are most likely exacerbating the problem. These characteristics are not representative of all modern coatings; instead, they are meant to explain, in a simplified way, the most common mechanisms for observed failure of paint films on NPS buildings:

- Waterborne coating systems form a film through coalescence and remain largely on the surface of the wood (Fig. 4). While they protect the outer surface, they do little to protect the underlying wood structure, which remains hygroscopic and unprotected.[16] Thus, any water entering a latex-paint system is free to absorb via capillary action into the wood structure.
- Many correctly applied waterborne paints (0.04–0.18 millimeters thick) allow considerable moisture movement through the film. This movement causes frequent changes in wood moisture content, resulting in expansion and contraction at the film/wood interface. These dimensional changes in the wood stress the paint film, which when paired with ultraviolet radiation, result in both microscopic and visible cracks that allow liquid water ingress.[17] If unaddressed, the rate of water infiltration will overwhelm the paint's ability to diffuse vapor out of the system, prolonging moisture in the substrate.[18]
- Many waterborne paints have high permeability ratings, but these are measured for film thicknesses ranging from 0.04 to 0.18 millimeters.[19] Increased film thickness results in decreased ability to diffuse water vapor, nullifying a reported permeability rating.[20] For wood that has gone through many painting campaigns, some of which have paint that is 0.5 to 1 millimeter thick, any water already in the wood or newly entering the system will be trapped (Fig. 5).

Characteristics of Linseed-Oil Paints

A number of characteristics of linseed-oil paint stand in contrast to the observed behavior of modern latex and acrylic waterborne coatings on NPS historic buildings.

Fig. 5. Many painting campaigns have led to overpainting and a film thickness of around 1 millimeter in areas on this wood sill trim board, 2020.

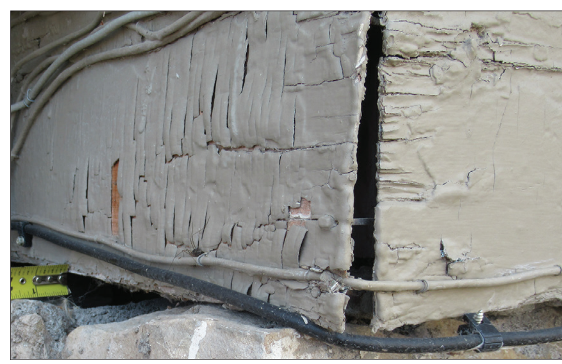


Fig. 4. From left to right, comparison of the absorption of purified raw linseed oil, purified linseed-oil paint, and modern latex paint seen from exposed end grain seven days after application. Raw linseed oil has been absorbed the most deeply; boiled linseed oil used in the linseed-oil paint has absorbed only shallowly. The latex paint is not absorbed at all and remains on the surface, 2020.

Linseed-oil paint systems are absorbed into the wood substrate, and they are able to form a surface film. The resulting hydrophobic environment beneath the surface film creates an additional zone of protection. If the surface film deteriorates to a point where liquid water could enter, it is less likely to be absorbed through capillary action because of the physical and chemical presence of linseed-oil molecules.[21] There is thus less of a chance to create favorable conditions for wood decay, particularly when maintenance is lax due to resource constraints.

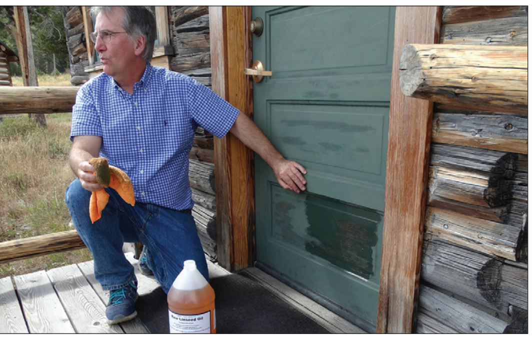


Fig. 6. A south-facing door at White Grass Ranch that was painted with linseed-oil paint has chalked after four years and is here being rubbed with purified linseed oil to refresh the paint film. Doors facing to the east, west, and north required re-oiling after eight years, 2016.

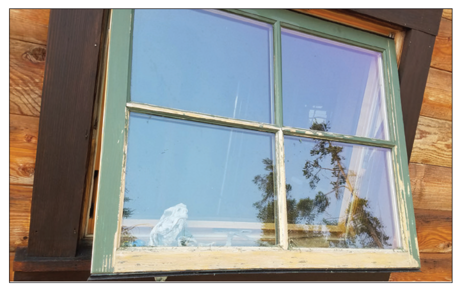
Linseed-oil paint weathers mainly by shedding pigment rather than by cracking or peeling. There are two reasons for this. First, the hydrophobic zone under the paint film results in fewer wood moisture fluctuations that cause mechanical stress and subsequent film failure.[22] Second, the film's structure is flexible and well suited to withstand wood dimensional changes.[23] However, over a period of about five to ten years, bonds linking oil molecules in the paint film break through exposure to oxygen and ultraviolet radiation. This process releases the pigment bound in the upper layers of the film that then sits freely on the surface, giving a chalky appearance while the underlying paint remains sound.[24] Wiping the surface with a thin layer of linseed oil rebinds the pigment and restarts the polymerization process of the weathered paint, restoring its integrity (Fig. 6). This weathering characteristic—chalking versus peeling—commonly allows linseed-oil paint films to last in excess of 15 to 30 years, depending on aspect, before requiring a new coat of paint. When fresh paint is required, old paint layers do not require stripping or scraping, only cleaning.

Linseed-oil paint rates high on the permeability and vapor-diffusion spectra.[25] This characteristic decreases opportunities for wood decay, as well as for paint failure like blistering and peeling resulting from vapor drive. The danger of paint buildup that would otherwise decrease permeability is mitigated by two characteristics. First, the viscosity of linseed-oil paint is much lower than that of modern paints, and it is applied in very thin layers. Second, weathered paint films require only re-oiling, rather than the addition of new layers of paint that could lead to increased film thickness.

Lastly, linseed-oil paint does not contain toxic additives like the biocides, levelers, driers, and solvents used in modern paints. This characteristic reduces hazards for workers and the environment, negating the need for strict safety measures, protective equipment, and controlled disposal. Linseed-oil brushes can be cleaned using water and linseed-oil soap (saponified linseed oil). While latex-paint brushes can also be cleaned with water, linseed-oil paint entering the water-treatment system contains vegetable oil, earth pigments, and minerals versus the plastic binders, petrochemical solvents, and synthetic pigments contained in latex paints.[26] The largest safety hazard associated with using linseed oil is the risk of spontaneous combustion in oil-soaked rags that have been wadded up and discarded. This hazard is mitigated by wetting oily rags and disposing of them in a closed metal container.

National Park Service Experience

In 2011 an NPS craftsperson working with the Western Center for Historic Preservation sought an alternative to latex paint after observing its premature failure on previous preservation projects (Fig. 7). His search led him to linseed-oil paint, and after researching its behavior and maintenance needs, he brought his findings to the director of the Western Center for Historic Preservation. The director greenlighted its use in the White Grass Ranch rehabilitation project, located in Grand Teton National Park in Wyoming (see Fig. 1).



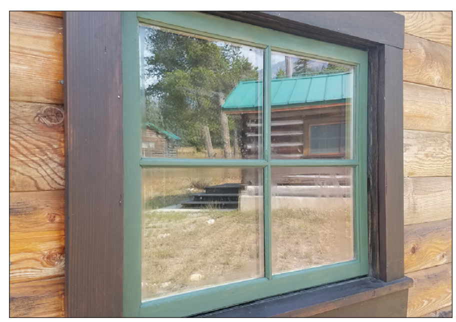


Fig. 7. Window at White Grass Ranch before the introduction of linseed-oil paint when waterborne latex paints were used, 2020. This window had early signs of paint failure, such as cracking and peeling, after two years. After 10 years, the paint had flaked off the bottom rail, portions of both stiles, and three muntins. This condition caused window glazing to fail in areas and required scraping and removal of loose paint, partial reglazing, and refinishing.

Fig. 8. Window at White Grass Ranch after refinishing with linseed-oil paint, 2020.

Starting in 2012, linseed-oil paint was used for all painted wood sash and doors at White Grass Ranch. Despite significant ultraviolet exposure and large daily and seasonal temperature swings, the linseed-oil painted surfaces have not failed. As expected, doors and sash on southern exposures chalked after five years. These were wiped with a fresh coat of boiled linseed oil, which reconstituted the pigment and refreshed the paint film. The paint continues to perform without defect. Doors and sash located on the western, eastern, and northern exposures were re-treated with a light coat of linseed oil after eight years. No surfaces with linseed-oil paint have required repainting (Fig. 8).

While there is potential for regularly incorporating linseed-oil paint as a preservation treatment in the NPS, there remain hurdles to its use. These challenges are shared throughout organizations and are not limited to the NPS. Other units of the NPS have started to experiment with linseed-oil paint for preservation projects in lieu of other types of modern coatings. The geographic distribution of NPS units provides opportunities to record the performance of linseed-oil paints over time in a wide range of climates and exposures.

Education and knowledge-sharing. Despite linseed oil being widely used in exterior paints until the 1950s, knowledge of linseed-oil technology has largely been lost. This presents a number of challenges.

- Those familiar with linseed oil are often distrustful of it because of their experiences with unpurified linseed oil, such as discoloration and mildewing. The first communication hurdle is explaining the difference between mass-marketed linseed oil and purified linseed oil.
- A related challenge comes with explaining the difference between raw and boiled oil, as these terms are often used loosely by linseed-oil manufacturers. There is a common misconception that a can of linseed oil from a hardware store with the term "boiled" on it is refined and therefore no different than purified linseed oil.
- There is difficulty in clearing up the confusion around linseed-oil paint and mildew. Purified linseed-oil paints available in the U.S. in the early 2000s did not contain zinc oxide and commonly mildewed in humid areas. For parks that used this particular paint, it is challenging to communicate that mildewing is not a foregone conclusion with all linseed-oil paints, only those that do not contain zinc oxide.
- Even when information regarding linseed oil is successfully shared, high turnover and lack of treatment documentation can erase education efforts. In a large agency like the NPS that experiences frequent personnel changes in field crews, it is difficult to ensure that wood elements painted with linseed oil do not get repainted with a latex or acrylic paint during a future project.

Practical constraints: money, time, and people. The constraints of limited project funding, tight work schedules, and small crews have made it difficult for some project managers to consider linseed-oil paint as a wood treatment.

- Linseed-oil paint requires significant up-front costs, both for the paint itself, as well as the time needed to prepare previously painted substrates. While the cost is recouped both during and after a project—through wider coverage per gallon (about two times as much as water-based paints), 100 percent dry volume (versus the typical 60 percent), decreased maintenance (re-oiling versus scraping and repainting), and a longer lifecycle (15 to 30 years versus 5 to 8 years)—it may not be possible for project managers to budget the up-front cost of using linseed-oil paint.[27]
- Using a linseed-oil paint system requires at least 24 to 48 hours between coats, with even longer drying times needed in areas with high relative humidity. Often, project managers are unwilling or unable to allow for this wait time or to alter project schedules to accommodate it. This problem is further exacerbated by the backlog of maintenance needs in the NPS and the urgency to move through projects at the most efficient rate possible.
- Linseed-oil paint requires a skilled painter for its application. Because of its thin consistency and lack of leveler additives, linseed-oil paint has a narrow margin for error and requires a craftsperson with experience for its appearance and performance (Fig. 9). Skilled painters are already rare in the NPS; skilled painters who also know how to apply linseed-oil paint are even more so.

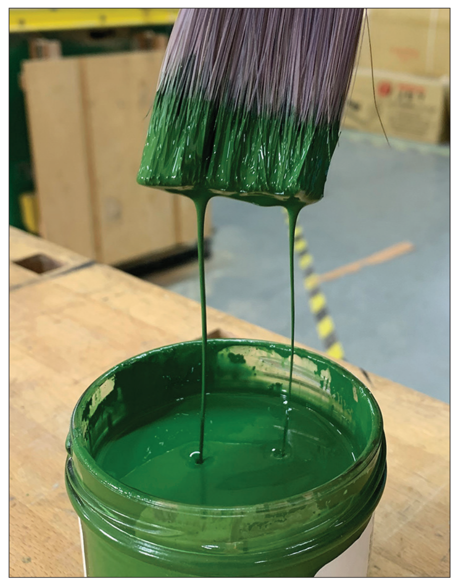


Fig. 9. Linseed-oil paint has an extremely thin consistency and must be applied in thin layers. The amount shown on the brush would cover approximately 4 square feet or more, depending on the condition of the substrate, 2020.

Considerations for Use of Linseed-Oil Paints

In spite of its increased usage, there are many unknowns with the performance of modern linseed-oil paint, as its renaissance in the U.S. is relatively new. Since historic formulations contained additives that are no longer used but would have improved their performance, such as lead, they cannot be used as a one-to-one comparison. There are no published studies that have systematically tested modern linseed-oil paints in different environments over a significant time period. There is a study forthcoming from Historic England that includes linseed-oil paints in its review of preservation coatings, but this will need to be extrapolated to climatic conditions in the U.S.[28]

Bearing this in mind, while linseed-oil paint is an effective treatment for some preservation projects, it has its limitations. Like any product, project managers must evaluate multiple considerations before deciding on its use.

Climate. Like modern paints, linseed-oil paint requires dry wood (less than 15 percent moisture content) and warm and dry weather for its application (60°F with less than 75 percent relative humidity). Unlike other modern paints, the weather window for applying linseed-oil paint must be adequate to accommodate its slower drying time. In areas that have sustained high relative humidity, the drying time of linseed-oil paint increases by multiple days. This requirement has important implications for mildew growth.

The elimination of mucilage and proteins and the addition of zinc oxide in linseed-oil paint decreases the risk of mildew attack. However, in the right conditions, mildew can grow on linseed-oil paint, especially before it dries. While definitive parameters for mildew growth remain unknown, studies suggest that high temperatures with liquid water and/or sustained high relative humidity above 75 percent paired with minute amounts of carbon sources, either from detritus, pollen, or wet linseed-oil paint, are enough to support growth.[29] While zinc oxide assists in retarding this growth, it may not be sufficient in climates where wet paint is subjected to these conditions over long periods of time. Linseed-oil paint applied during periods of sustained high humidity and temperatures, common in the mid-Atlantic, the Southeast, and the coastal Pacific Northwest, are at a higher risk for mildewing than paint applied in regions with reliable periods of dry weather.

Studies indicate that once linseed-oil paint has fully dried, mildew cannot use the polymerized oil as a food source.[30] Instead, mildew growing on dried linseed-oil paint is most likely the result of liquid water and/or high relative humidity and blown organic matter sitting on the film, especially in areas without much sunlight. This phenomenon is not unique to linseed-oil paint: It occurs on latex and acrylic paints as well.[31]

Since it is difficult to guarantee weather windows for most regions in the U.S., it is always recommended to paint on-site test panels to determine drying times for various aspects and what adverse effects may result from unexpected rain or temperature swings during the dry-time window.

Substrate preparation and prior treatments. Linseed-oil paint works best on clean substrates with a moisture content of less than 15 percent. If there are existing paint layers, they may cause differential absorption of the paint and may result in a mottled appearance. Additionally, if existing paint layers are those that either are impermeable or if their thickness results in impermeability, the problem of vapor diffusion will continue to be an issue. While it is possible to have good performance from linseed-oil paint applied over existing paint—provided it has been scraped and cleaned as much as possible—expect that it will perform worse than if the substrate was clear. If a project does not have the budget for up-front substrate preparation necessary for linseed-oil paint to perform well, a different coating should be considered.

Painting technique. Linseed-oil paint has a very different consistency than the modern paints familiar to most craftspeople; it is thin to the point of feeling watery on the brush. This consistency makes it difficult for many craftspeople to adapt to its application, which must be in very thin layers. Layers of paint that are too thick often have long dry times, wrinkle, mottle, or most importantly, perform poorly. Thick linseed-oil paint can result in coats that never dry fully or cure, negating the benefits of the paint.[32] A project using linseed-oil paint requires a painter who has experience painting with linseed-oil paint or is willing to adapt to the proper painting technique.

Number of coats. A priming coat of purified linseed oil—either raw linseed oil on its own or linseed-oil paint diluted with raw linseed oil—is recommended before proceeding with linseed-oil paint. In addition to its hydrophobic and conditioning properties, primer coats keep the paint from being drawn deep into the wood, which would otherwise necessitate additional coats for coverage. As with modern paints, the minimum number of coats for linseed-oil paint is generally two to three, although more may be needed for a light color. A test panel or swatch is recommended to accurately determine the number of coats needed for a particular shade of paint.

Workflow and time frame. A coat of properly applied linseed-oil paint generally takes a minimum of 24 to 48 hours to dry to the touch. This window will increase in areas of high relative humidity. If painting movable elements, such as doors or windows, workers should consider drying them in a heated room if possible. Regardless, present-day project workflows are not structured to allow for this expanded time frame. To be successful, adequate drying time must be built into workflows rather than overlaid on top of them, which could disrupt established project patterns. Changing workflow expectations may not always be realistic, even when possible.

Conclusion

Purified linseed-oil systems are a promising preservation treatment and a viable option for use on historic wood resources. However, they are not a preservation panacea. When selecting linseed-oil paint, it is imperative that purchasers understand what they need and what they are buying. Good specifications are key to acquiring and applying the optimal product for a given project. Climate, substrate preparation, access to skilled labor, workflow, and project funds must all be considered. The potential benefits of longevity, ease of maintenance, cost effectiveness over a building's life cycle, and environmentally responsible formulations are well worth serious consideration for preservation projects, as well as deserving of further experimentation and investigation.

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Notes

1. Whitman Eastman, *History of the Linseed Oil Industry in the United States* (Minneapolis: T. S. Dennison, 1968), 123, https://www.ag.ndsu.edu/agnic/flax/Eastman/ch%205.pdf. Ian C. Bristow, "House Painting in Britain," in *Paint in America: The Colors of Historic Buildings*, ed. Roger W. Moss (Washington, D.C.: The Preservation Press, 1994), 43.

2. Eastman, 131. Abbot Lowell Cummings and Richard M. Candee, "Colonial and Federal America: Accounts of Early Painting Practices," in *Paint in America: The Colors of Historic Buildings*, 18. Bill Reutz, "Linseed Oil Lives On," *American Paint & Coatings Journal* 79, no. 12 (1994): 21.

3. David Ernhart, "Paints Based on Drying Oil Media," in *Proceedings of Painted Wood: History and Conservation Symposium*, ed. Valerie Dorge and F. Carey Howlett (Singapore: J. Paul Getty Trust, 1994), 22, https://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/paintedwood1.pdf. Harriet A. L. Standeven, *House Paints 1900–1960* (Los Angeles: Getty Conservation Institute, 2011), 30.

4. Reutz, 21. Standeven, 33.

5. Here, the term "cold-pressed" refers to mechanically crushing flax seeds to extract linseed oil. While this results in a smaller yield than other methods, oil extracted in this way contains the least amount of impurities. The highest-quality linseed oils are cold-pressed. Other methods of oil extraction involve the use of solvents, which results in a high yield of oil and a higher amount of impurities. To clean or wash cold-pressed oil, it is allowed either to sit for a couple seasons or mixed with water and agitated. As the mixture settles, protein and mucilage separate from the oil and are deposited in layers called "foots." Pure linseed oil is then decanted from the mixture.

6. Ernhart, 19.

7. Kurt Weise, "Attack of Linseed Oil Paints by Mould Growth," abstract, *Paint and Varnish Production Manager* 10 (1934): 12–16, Getty AATA Online.

8. Mark Knaebe, *Paint, Stain, Varnish, or Preservative? It's Your Choice* (Madison, Wisc.: U.S. Dept. of Agriculture, U.S. Forest Service, 2013), https://www.fpl.fs.fed.us/documnts/finlines/finishline_mknaebe_2013_014.pdf.

9. This exposure can range from ultraviolet radiation to flash heating over a heat source.

10. Kimberly D. Dugan and Ronald W. Anthony, *Understanding Traditional and Modern Paints and Stains for Exterior Wood* (National Center for Preservation Technology and Training, 2014), 53, https://www.ncptt.nps.gov/blog/understanding-traditional-and-modern-paints-and-stains-for-exterior-wood-2014-01/.

11. Not all exposed wood requires oiling. Many old-growth logs and lumber remain stable in their native environment without the need for any treatment. Oiling lumber can be beneficial, especially for new-growth lumber, in chronically wet environments in order to limit liquid water absorption or in very dry, high alpine environments in order to prevent excessive weathering.

12. Natalie Yon-Eriksson (owner of Earth+Flax), discussion with the authors, July 2021.

13. Ernhart, 17–22.

14. Robert A. Zabel and Jeffrey J. Morrell, *Wood Microbiology: Decay and Its Prevention*, 2nd ed. (London: Elsevier, 2020), 391–392.

15. Brian P. Baker and Jennifer A. Grant, *Linseed Oil Profile: Active Ingredient Eligible for Minimum Risk Pesticide* (Geneva, N.Y.: New York State Integrated Pest Management and Cornell Cooperative Extension, 2018), 6, https://ecommons.cornell.edu/handle/1813/52630. Miha Humar and Bostjan Lesar, "Efficacy of Linseed- and Tung-Oil Treated Wood Against Wood Decay Fungi and Water Uptake," *International Biodeterioration and Biodegradation* 85 (2013): 223–227, https://doi.org/10.1016/j.ibiod.2013.07.011.

16. Ralph M. Nussbaum, E. John Sutcliffe, and Anne-Charlotte Hellgren, "Microautoradiographic Studies of the Penetration of Alkyd, Alkyd Emulsion and Linseed Oil Coatings into Wood," *Journal of Coatings Technology* 70, no. 878 (1998): 53, https://doi-org.proxy-um.researchport.umd.edu/10.1007/s001070050445.

17. Mari de Meijer and Holger Militz, "Moisture Transport in Coated Wood, Part 2: Influence of Coating Type, Film Thickness, Wood Species, Temperature and Moisture Gradient on Kinetics of Sorption and Dimensional Change," *Holz als Roh- und Werkstoff* 58 (2001): 468, https://doi-org.proxy-um.researchport.umd.edu/10.1007/s001070050461.

18. J. A. Graystone, "Moisture Transport Through Wood Coatings: The Unanswered Questions," *Surface Coatings International Part B: Coatings Transactions* 84, no. B3 (2001): 179, https://doi-org.proxy-um.researchport.umd.edu/10.1007/BF02700396.

19. Meijer and Militz, 468.

20. Graystone, 181.

21. Dugan and Anthony, 53.

22. Nussbaum, Sutcliffe, and Hellgren, 49.

23. Standeven, 18–19.

24. Dugan and Anthony, 23. Ernhart, 22.

25. Pirjo Ahola, "Moisture Transport in Wood Coated with Joinery Paints," *Holz als Roh- und Werkstoff* 49 (1991): 430–431, https://doi.org/10.1007/BF02619465.

26. Some craftspeople familiar with linseed-oil systems prefer to add pure balsamic turpentine or mineral spirits to their mixtures in various ratios to thin the oil. This would make the mixture unsuitable for the water-treatment system.

27. Dry volume is the percentage of paint that remains on a surface after the film has dried and diluents (water, solvents, etc.) in the paint mixture evaporate.

28. More information on the Historic England paint-durability study can be found at "Materials and Techniques," Historic England, updated June 3, 2020, https://historicengland.org.uk/research/current/conservation-research/materials-and-techniques/#Section7Text.

29. Loes H. M. Peeters, Hendrick P. Huinink, Benjamin Voogt, and Olaf C. G. Adan, "Oil Type and Cross-Linking Influence Growth of Aureobasidium Melanogenum on Vegetable Oils as a Single Carbon Source," *Microbiology Open* 7, no. 6 (2018): 8, https://doi.org/10.1002/mbo3.605; Zabel and Morrell, 390–391.

30. Peeters, Huinink, Voogt, and Adan, 2–11.

31. Zabel and Morrell, 295–296.

32. Ernhart, 22.

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