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A comparison of Green Varnish Rescue and two traditional solvents used in painting conservation

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ABSTRACT

This study assesses Green Varnish Rescue, a nonflammable, eco-friendly solvent for removing aged varnish from oil paintings, comparing its performance to traditional solvents (TACO2 and a DMSO/MEK/acetone blend). Testing on two naturally aged paintings demonstrated equivalent cleaning efficacy but with superior safety and sustainability. Green Varnish Rescue caused minimal pigment disruption, left negligible residue, and required fewer applications, reducing both material costs and labor time. Its non-toxic formulation showed the lowest environmental impact, emitting low volatile organic compounds and being readily biodegradable. Economic analysis revealed 80% cost savings over conventional solvents due to lower purchase price and reduced waste disposal requirements. UV and XRF analysis confirmed that there were no long-term effects on the paint layers. These results establish Green Varnish Rescue as an optimal solution for conservators prioritizing both budget constraints and ecological responsibility, offering professional-grade treatment without compromising operator safety or environmental standards. The solvent's combination of affordability, cleaning efficiency, and sustainability meets the growing demand for green alternatives in cultural heritage conservation.

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Preface

This thesis concludes my studies in the Conservation program at the University of Gothenburg and reflects both the theoretical training and hands-on experience I have gained in the program. The project was shaped by my growing interest in solvent-based varnish removal and the possibilities of safer, greener alternatives in conservation practice.

I would like to thank my supervisor, Kristina Frenguelli, for her generous guidance and encouragement, as well as for providing the solvents and materials used in this study. I am also grateful to Viktor, Christina, and Mattias, my internship mentors, for their support and insights during practical work. Special thanks to Xia Zhenyuan for teaching me photographic documentation techniques and for our valuable discussions on chemistry, and to Jia Yiming for helpful conversations about solvent toxicity. I also thank Sebastian for his assistance with the XRF test.

Finally, I am deeply grateful to my family, especially Yi Mengyuan, for their continuous support and companionship during my studies.

Gothenburg, June 2025
Shuyu Xi

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1 INTRODUCTION

1.1 BACKGROUND

Varnish is typically applied as a transparent protective layer over oil paintings, serving both aesthetic and preservative functions. As early as the eighteenth century, “essential varnishes” had been recognized as particularly suitable for painting restoration and became part of the standardized procedures developed through experimental practice (Conti & Glanville, 2007, p.171). Varnishes exist in various types beyond resin-solvent mixtures, for example, natural oils or mastic. Varnish’s primary role is to return the original state of the colors and to create a barrier in two ways; the first is physical protection to keep the object clean, and the second is to protect it from chemical attacks in the environment, such as water and specific gases like hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and oxygen (O_2), that cause oxidation and other forms of corrosion (Newey et al., 1992, p. 115). A well-formulated varnish should preserve original colors without altering them or creating excessive gloss, while remaining clear and transparent itself (Conti & Glanville, 2007, p.171-173).

Varnish cleaning is a crucial step in the restoration of oil paintings. One of the most common tasks in oil painting restoration is the removal of aged varnish and previous retouching. Over time, varnish tends to yellow and lose its transparency due to aging. To maintain protection of the original paint layer, conservators often remove the aged varnish and apply a fresh coating (Matteini et al., 2016, p.213).

“For cleaning, conservators must find a solvent which:

- does not dissolve to a significant extent any part of the object.
- dissolves the dirt or whatever is holding it in place.
- dries out, but not so quickly that it leaves dirt infiltrated into the object.” (Moncrieff & Weaver,1992, p.52)

Moncrieff and Weaver assert that conservators should “stress safeguarding the object rather than focusing on attacking the unwanted material” (1992, p.52). As varnish ages, its chemical characteristics change. Natural resins such as dammar and mastic become more polar, requiring more polar solvent mixtures for effective removal (Feller & Curran, 1975, p.18).

Since each painting’s varnish may vary in resin type, concentration, or degree of aging, it is often necessary to mix different organic solvents. The goal is to create a solution strong enough to dissolve the top layer of varnish, yet gentle enough not to damage the original paint layer underneath.

Many organic solvents used in conservation are volatile, flammable, and in some cases even toxic (Moncrieff and Weaver 1992, pp.62-71; Horie, 2011, p.77). At sufficiently high concentrations, they can adversely affect the central nervous system and may irritate the respiratory tract and mucous membranes. People who have been sensitized to certain solvents may experience these effects even at much lower exposure levels (Horie, 2011, p.79). Some solvents are also liked to reproductive health risks and can contribute to soil and water contamination, including the pollution of groundwater (Bruckner et al., 2019, p.1165). For these reasons, conservators need to work in well-ventilated studios or use protective masks that filter organic vapors. Additionally, certain solvents and oils may contain peroxides that can spontaneously ignite used cloths as they dry. Also, to prevent fire harzards, such waste should always be stored in fireproof containers until proper disposal (Horie, 2011, p.78). Thus, it’s essential to select and formulate solvents according to the specific properties of each varnish layer.

A sustainable solvent should pose less risk to humans and the environment throughout its life cycle: from production to disposal. Those derived from agricultural crops are known as bio-solvents. A solvent is also considered sustainable if it works effectively in small amounts, reducing both waste and exposure (Fife, 2021, pp.16-17,62).

Before beginning cleaning, solubility tests are usually carried out on a small area of the painting to assess material solubility and to choose a suitable solvent mixture and application method. It is best to use theoretical models to predict the solubility of these materials (Baij et al.,2020, p.6). Due to the complexity of formulating solvent mixtures, the software *Trisolv* [1]5.5 was developed in the 1990s as a predictive tool. It helps conservators formulate solvents tailored to the specific characteristics of a varnish. The mixtures can be made from two or three organic solvents, typically including alcohols, hydrocarbons, and ketones.

1.2 PREVIOUS RESEARCH

The earliest protective varnish has been reported on Egyptian wooden artifacts from over 4000 years ago, composed mainly of natural resins and oil-based gums. The earliest known cleaning methods, recorded in 1632, used simple materials such as warm water, soap, vinegar, and alcohol, applied with a cloth or sponge. These treatments were often ineffective or too harsh, sometimes damaging both the varnish and the underlying paint layer (Caley, 1990, pp.70–71).

In a handbook guiding conservators in selecting sustainable solvents, Fife (2021, p.36) describes a method for predicting the removal of different organic materials using solvent mixtures. This approach focuses on three types of solvents: alcohols, ketones, and alkanes, but excludes water. The method is based on the Hansen Solubility Parameters (HSP), which visualize dispersion forces (fd), polarity (fp), and hydrogen bonding (fh) on a triangular diagram, also known as the Teas chart (Hansen, 2007, p.143). Fife considers it to provide reliable results when interpreted as volume-weighted averages (2021, p.36). When evaluating single or mixed solvents, they can be plotted on the Teas chart to visualize their position (Fife, 2021, p.40). According to the "like dissolves like" principle, the closer a solvent is to the varnish on the Teas chart, the higher the likelihood of solubility (Baij et al., 2020, p.6). However, Özdemir & Güner argue, based on thermodynamic calculations, that the "like dissolves like" principle alone is insufficient for predicting solvent effects on polymers (Özdemir & Güner, 2007, p.3091).

However, the Teas chart also has several limitations. For example, it cannot quantitatively or qualitatively predict the swelling behavior of solvents on oil paint layers (Baij et al., 2020, pp.8–9). While Hansen solubility parameters are originally three-dimensional, comprising δd (dispersion), δp (polarity), and δh (hydrogen bonding), the Teas chart compresses these values into a two-dimensional triangular diagram. As a result, solvents with very different properties may appear close on the chart, potentially misleading the conservator (Stavroudis & Blank, 1989). Horie also emphasizes the limitations of the Hansen–Teas model. First, it does not account for polymers with strong hydrogen bonding. Second, it fails to reflect the influence of molar volume. Third, it overlooks the impact of temperature on both the solvent and polymer behavior (Horie, 2011, p.75). Given these factors, the chart's predictive power is limited, and its results should be considered only as general guidance.

[1] Interactive triangle of solvents and solubilities, available for download at: http://iscr.beniculturali.it/pagina.cfm?umn=297&uid=505&usz=1

Therefore, Hansen's Teas charts are best used as an initial reference tool and must be interpreted with caution.

Baij et al. further point out that cleaning varnish from oil paintings is inherently complex, as it involves polymer chemistry. The polymeric structure of oil paint is not stable; it changes over time due to factors such as pigment composition, light exposure, oxidation, and the formation of metal soaps. As a result, the cleaning effectiveness, risks, and limitations depend on the specific properties of the polymer network, including its degree of cross-linking, polarity, concentration of plasticizers, and the presence of metal ions such as zinc or lead. Solvents can induce both temporary and long-term changes to the paint film, many of which remain unpredictable. These may include increased brittleness or losing vital components, making outcome predictions difficult (Baij et al., 2020).

Understanding the polymeric behavior of oil paint, solvent safety, and evaporation rate is also an important consideration. Fife recommends consulting the CHEM21 Solvent Selection Guide to assess the health and environmental safety of selected solvents. Solvent evaporation rates must also be considered, as they significantly affect the dried film characteristics of the polymer (Fife, 2021, p.41).

Ferguson et al. (2024) define sustainable solvents as non-toxic, low in volatility, and non-flammable. However, even when using sustainable solvents, there is a risk of residual solvents remaining on the painting surface, potentially causing long-term effects. For this reason, it is essential to remove any remaining solvent as thoroughly as possible (Stoner & Rushfield, 2021, p.526). Isooctane, an aliphatic hydrocarbon, does not form azeotropes with water and has very limited solubility for polar substances, It is non-ionizing, non-dissociating.These properties make isooctane suitable and safe for use as a diluent (Masschelein-Kleiner, 1994, p.61).For this reason, isooctane was selected in this study to aid in the removal of residual solvent after cleaning.

Recent research by Melchiorre et al. (2023) demonstrated that γ-valerolactone, (2,2-dimethyl-1,3-dioxolan-4-yl) methanol, and 2-ethylhexyl pelargonate can respectively replace acetone, ethanol, and iso-octane in solvent mixtures.

The aged varnish is originally a solid structure that has already cured, with tightly packed molecular arrangements. When a solvent meets the aged varnish, the varnish does not immediately dissolve completely, because cross-linking or aging has made it very stable and difficult to dissolve.

What happens is: The solvent molecules slowly penetrate between the varnish molecules, pushing some of them apart, causing the varnish to swell, but without fully dispersing it down to the molecular level. This swollen state results in the formation of a coacervate dispersion: the molecules begin to loosen and show some fluidity, but they still maintain mutual attraction and do not separate into freely dispersed small particles (as would occur in a solution). Because this state is neither a completely hard solid nor a fully dissolved solution, the varnish becomes softer, allowing it to be mechanically removed using a cotton pad or gauze (Masschelein-Kleiner, 1994, p.40).

1.3 AIM AND GOAL

This study aims to explore the dissolving capabilities of different solvents on oil painting varnishes and to evaluate their safety in conservation practice. The research focuses on identifying sustainable solvents that can effectively remove aged varnishes without harming the underlying paint layers, while also reducing environmental impact and health risks for conservators. In addition, sustainable solvents offer practical benefits in conservation work, including improved biodegradability of waste materials, lower storage risks and costs, and the potential to reduce investment in studio ventilation systems.

The goal of this research is to analytically investigate the efficiency and effectiveness of varnish removal treatment on the painting "*Landscape*". By utilizing the predictive capabilities of the *Trisolv* software, this study will test the solubility of two selected sustainable solvents while also evaluating their volatility, flammability, toxicity, and biodegradability.

1.4 PROBLEM FORMULATION AND RESEARCH QUESTIONS

Given the many variables involved in solvent selection, Hansen's Teas charts should be regarded as a preliminary predictive tool and interpreted cautiously. Previous studies on sustainable solvents have mainly focused on mock-ups or aged varnish layers. In this research, the solubility of fresh varnishes is compared with that of naturally aged ones, using one sustainable solvent and two traditional solvent mixtures.

The sustainable solvent *Green Varnish Rescue*(GVR), developed by YOCOCU, consists of Dioxolane, Texanol (TOU), and Dibasic Ester (DBE). It is reportedly non-toxic, non-flammable, low in volatility, and biodegradable. A study by Macchia et al. (2021) found that GVR effectively removes varnishes such as dammar, retoucher, and paraloid. Compared to some traditional toxic solvents, it causes less color change and swelling, making it a more environmentally friendly option. Additionally, it is designed to exhibit moderate swelling power (f_d) within a safe working range (Macchia et al., 2021). In contrast, commonly used organic solvents tend to be flammable, volatile, toxic, and environmentally harmful. Their use in conservation often requires expensive storage facilities, advanced ventilation systems, and strict waste management procedures.

If sustainable solvents, such as *GVR* can achieve comparable cleaning efficiency to conventional solvents, they may promote more sustainable conservation practices and help reduce studio operational costs. This study compares the cleaning performance of *GVR* with two traditional solvent mixtures: TACO2 and a 1:1:1 blend of dimethyl sulfoxide (DMSO), methyl ethyl ketone (MEK), and acetone. Both aged and fresh varnish layers on oil paintings are included in the evaluation. The following research questions are addressed:

1. How effective is *GVR* in removing aged and fresh varnish?
2. Can *GVR* replace traditional solvent mixtures to clean aged varnish?

1.5 SCOPE AND LIMITATIONS

This study focuses only on two oil paintings where the paint layers are fully dried, both over 50 years old. One painting has an aged varnish layer of unknown type. The other painting, initially unvarnished, was coated with synthetic dammar resin for testing. Results may vary with different varnish types and solvent interactions.

The tests are limited to three solvent mixtures: GVR, TACO2, and DMSO/MEK/Acetone (1:1:1). Single-component solvents were not included. Therefore, results only reflect the performance of these organic solvents within this specific context.

Other removal methods, such as gel or soap-based carriers and physical techniques (Smith & Mills, 1990), were not used. This study only included three removal methods: cotton swab dabbing, swab rolling, and facial tissue coverage, with results observed and recorded accordingly.

1.6 THEORETICAL FRAMEWORK

The study is a case-based investigation that integrates both qualitative and quantitative experiments to evaluate the removal performance of one sustainable solvent and two traditional organic solvents. A hypothetico-deductive approach is applied to assess selected variables and draw preliminary conclusions about the relationship between solvent properties and their interaction with aged varnish layers (Patel & Davidson, 2014, pp.51-57, Wallén, 1996, p.47)

In the painting "*Landscape 1*", previous retouching has noticeably discolored, making it visually distinct. Additionally, the varnish layer has aged and significantly yellowed. According to Brandi's restoration theory, any added or changed parts that risk falsifying the historical reading of a work should be removed, unless removal poses a risk of damage to the original artwork (Brandi & Basile, 2005, p.73).

Muñoz Viñas points out that "the decision about removing specific layers of the painting while leaving others is completely subjective." (2009, p.50). He introduces the concept of "minimal intervention", suggesting conservators should always find a careful balance to avoid unnecessary alterations. He believes conservation treatments should minimize loss of historical evidence, aesthetic qualities, and original materials (Muñoz Viñas, 2009, pp.53-57). Thus, the principle guiding this experiment is to remove aged varnish effectively, while minimizing any damage to the painting's historical integrity and original layers.

1.7 METHOD

This study is based on two case studies. All solvents were selected using solubility prediction software. Cleaning tests were designed using both qualitative and quantitative approaches. The results were recorded based on swelling time, cleaning effectiveness, solvent toxicity, and the conservator's handling controllability and observations. Visual light and UV light photography, as well as X-ray fluorescence (XRF), were used to document the cleaning results. Toxicity analysis based on CHEN21 and LD50 data — from the solvent's Material Safety Data Sheets (MSDS). The performance of various solvents was compared on both aged and fresh varnish layers.

2 MATERIAL AND EXPERIMENTAL METHODS

Oil paintings can take years to dry thoroughly (Taft et al., 2000, p. 23). Two paintings (Fig.1), each over fifty years old, were therefore selected to assess aging effects and to compare solvent cleaning performance on different varnish conditions. One painting retained its original, naturally aged varnish layer; the other had never been varnished but was subsequently coated with two layers of modern synthetic varnish.

The solvents used in this study were chosen based on their solubility parameters and common use in conservation. Cleaning trials were carried out under controlled humidity and temperature. All solvent applications were carried out by timed swabbing and solvent-loaded Japanese paper. Varnish removal was measured using the Fife solvent-star rating system and documented with photographic records. Under-paint impact was monitored by X-ray fluorescence (XRF) analysis. Solvent evaporation rates were determined gravimetrically for each formulation under the same environmental conditions. Most of the images were taken by the author; other sources are indicated separately.

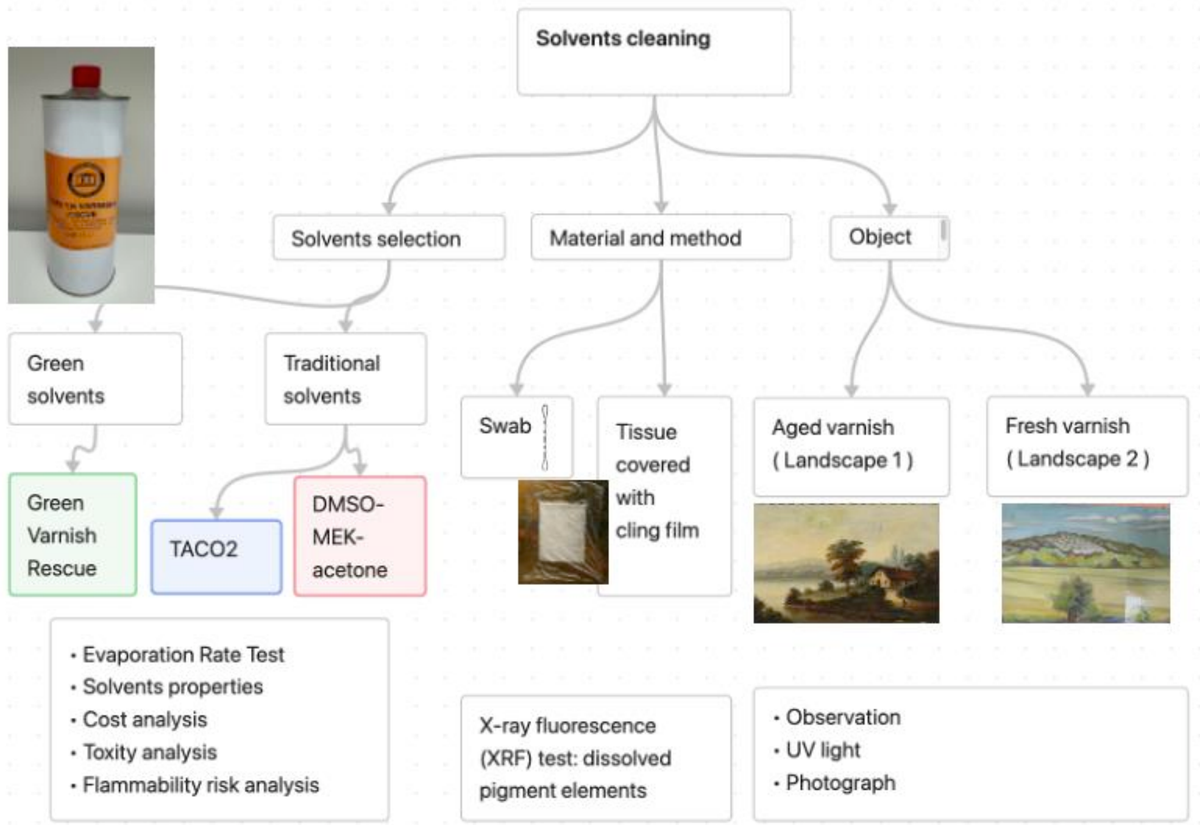


Figure 1. Experimental method flow chart

2.1 Two Paintings Used for Testing

The painting *Landscape 1* portrays a woman standing outside a house (Fig. 1). It was acquired in 2024 from Borås Auktionshall, while the artist is unknown. The work is oil on canvas mounted on a wooden panel, with a heavily aged varnish layer. The surface shows craquelure and several old retouches that have discolored. It is likely to be dated to the late 19th or early 20th century.

Figure 2. Landscape 1 before treatment. Foto: Borås Auktionshall

The painting *Landscape 2* (Fig. 3) was bought in 2025 from a private collector. The canvas bears no ground layer, with oil paint applied directly onto the fabric layer. It is signed Urho Alex Zacharov, a Finnish artist, and dated 1914. It has no visible signs, leaving the surface very dry and matte with no traces of previous restoration.

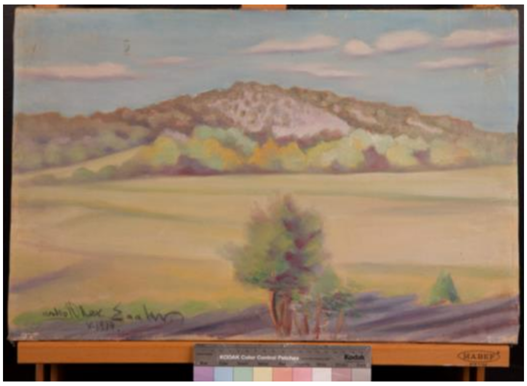


Figure 3. The original unvarnished painting Landscape 2

Figure 4. Landscape 2 was varnished with a two-layer vertical strip from top to bottom.

Two coats of Daler/Rowney damar varnish were freshly applied with a large brush in vertical strokes from top to bottom on the right (Fig. 4). This varnish is a synthetic resin, and each layer was allowed to dry for six days.

2.2 GVR, TACO2 and DMSO blend

GVR is the sustainable solvent (Figs. 5 and 6). TACO2 and DMSO blend are traditional solvents, and both show medium evaporation rates. TACO2 consisted of an isopropanol-n-Octane-acetone blend (15%:46%:39%) (Fig.7); and the DMSO blend was mixed in a 1:1:1 ratio (Fig.8).

Figure 5. GVR, 1-kilogram bottle.

Figure 6. Safety label on the side of the bottle.

GVR carries only the exclamation-mark hazard pictogram and has no flammability or toxicity labels (Fig. 6).

Figure 7. Photo of the solvent bottles for dimethyl sulfoxide (DMSO), ethyl methyl ketone (MEK), and acetone used in the preparation of the TACO2 bland preparation.

Figure 8. Photo of the solvent bottles for dimethyl sulfoxide (DMSO), Ethyl methyl ketone (MEK) and acetone used in DMSO–MEK–acetone bland preparation.

2.2.1 TACO2

Trisolv 5.5 provides nine traditional solvent mixtures, labeled TACO1 to TACO9, which are particularly effective for dissolving aged natural varnishes. First, all high-volatility solvents were excluded, since our goal is to identify low-volatility yet effective solvents. This left TACO2, 5, and 8. However, on the Teas chart, TACO5 and 8 plot close to the oil region, a risk of pigment dissolution. Therefore, TACO2 (Tab.1) was chosen as the test solvent.

Table 1. Ingredients, ratio, and molecular formula of the three solvents.

Solvents	Ingredients	Ratio	Molecular formula
GVR	dioxolane	unknown	$C_3H_6O_2$
	TOU	unknown	$C_7H_{16}O_4$
	DBE	unknown	$C_9H_{16}O_4$
TACO2	isopropanol	15%	C_3H_8O
	n-octane	46%	C_8H_{18}
	acetone	39%	C_3H_6O
DMSO-MEK-acetone blend (1 : 1 : 1)	DMSO	33.3%	C_2H_6OS
	MEK	33.3%	C_3H_6O
	acetone	33.3%	C_3H_6O

2.2.2 DMSO-MEK-acetone blend (1 : 1 : 1)

A 1:1:1 blend of DMSO, MEK, and acetone is highly effective for removing polar, aged varnishes. Solvents with higher dielectric constants better weaken ionic attractions and promote dissociation. DMSO, with a dielectric constant of 48.9, is a powerful polar (dissociating) solvent that excels at breaking intermolecular forces and dissolving polar materials (Masschelein-Kleiner, 1994, p. 50). MEK and acetone are also strongly polar, enabling them to exert strong interactions on ions and other polar molecules, making them highly effective at dissolving oils and heavily oxidized resins (Masschelein-Kleiner, 1994, pp.52-53). However, this strong polarity also raises the risk of dissolving the underlying oil paint.

The solubility of the three solvents can be predicted using the *Trisolv* 5.5 software. The f_d axis represents dispersion forces, f_p represents polarity, and f_h represents hydrogen-bonding capacity. Oil and wax plot toward the lower-right corner, indicating relatively low polarity. Each solvent is indicated by a dashed outline in the diagram (Fig. 9): GVR appears as a light-green dashed region; TACO2's position, readily obtained from the *Trisolv* 5.5 database, is shown as a small blue dot; and the DMSO blend is marked in red dot.

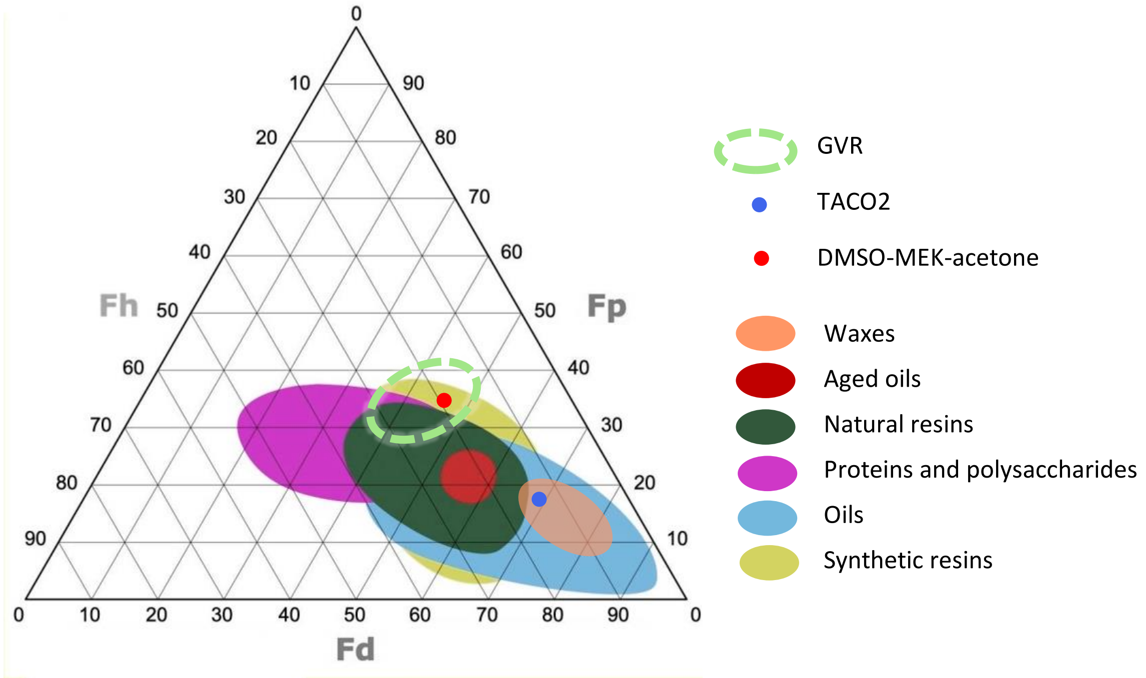


Figure 9. Positions of the three solvents on the Teas triangular diagram. GVR is outlined in light-green dashes, TACO2 in blue a dot, and the DMSO blend in red dot. Photo: Maurizio Coladonato, Istituto Superiore per la Conservazione ed il Restauro (ISCR).

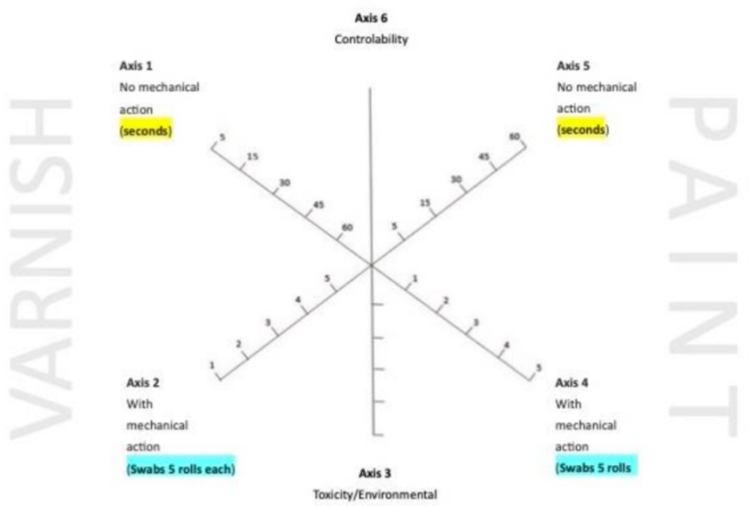
The Teas chart reveals distinct polarity characteristics among the solvents: both GVR (Macchia et al., 2017, p.20) and the DMSOblend demonstrate higher polarity than TACO2. Notably, GVR exhibits broader compatibility with both natural and synthetic resin regions compared to the DMSOblend (red dot). TACO2 (blue dot), by contrast, shows affinity only for synthetic resins. Feller and Curran's (1975, p.18) finding that aged varnishes increase in polarity over time, a phenomenon represented by upward displacement on the chart that necessitates the use of higher polarity solvents for effective cleaning.

2.3 Solubility Test 1 – Solvent Star Diagram for Recording Efficiency

To evaluate solvent efficiency, the time at which the varnish begins to swell is recorded experimentally. In this study, the Fife Solvent Star (Fig. 10) methodology was applied. It was developed by Fife (Stichting Restauratie Atelier Limburg) and uses a star diagram to record both the qualitative aspects, such as controllability and perceived effectiveness by conservators, and the quantitative aspect of efficiency as measured by swelling time (Fife, 2020). Selecting the optimal solvent for a painting often requires multiple trials. The Fife solvent star method summarizes the properties of each candidate in a single radar plot.

Painting Description:
Title:
Artist:

Painting basic information



- All values are plotted on 6 axes (low scores lie near the center, high scores toward the rim).
  1) Varnish–Time: Swab contact duration (s) until varnish first dissolves
  2) Varnish–Rolls – Number of swab rolls required to begin dissolving varnish
  3) Toxicity – more toxic solvents plotted closer to the center.
  4) Pigment–Time: Swab contact duration (s) until paint layer begins to soften or lift
  5) Pigment–Rolls: Number of swab rolls required to begin extracting pigment Operator
  6) Control – Ease-of-use rating (1 = very difficult; 6 = very easy)
- Connect the points: **larger hexagon area** = more efficient solvent.
- One chart per painting.

Solvent	Ratio (if mixture)	Colour Legend	Quantity solvent (ml)	
			spot A	spot B

Record for each solvent:

- Solvent types and Mixing ratio
- Color codes used on the chart

Date of testing:
Notes/comments:

Selected Solvent/Approach:

- Summarize and comments
- Criteria and rationale for the final

Figure 10. The left side shows the Fife Solvent Star chart; the right side provides instructions on recording the data.

Detailed instructions for the use of Fig. 9.

- The top section lists the painting's basic information.
- The second section is the 6 axes record: values near the center indicate low performance, while those toward the perimeter indicate higher performance.
  - Axes 1 and 2 track varnish removal only.
  - Axes 4 and 5 track pigment loss only.
  - On axes 1 and 4, the time (in seconds) is recorded until varnish or pigment first dissolves under a swab.

- Axes 2 and 5 register the number of swab rolls required to initiate varnish or pigment removal. Accounting for the mechanical action of rolling helps strip away swollen varnish and improves cleaning efficiency.
- Axis 3 rates solvent toxicity, using CHEM21 data as recommended by Fife (2021, p.44).
- Axis 6 captures the operator's subjective sense of control over the cleaning.

- The third section lists each solvent's type, its mixing ratio, the volume used, and the color assigned to it on the six axes.
- The bottom section summarizes any issues encountered during testing and outlines the reasoning behind the final solvent choice. Conservators can quickly review the entire testing sequence and the combined qualitative and quantitative assessments by consulting the Fife Solvent Star.

The test areas comprised the painted tree on the house in *Landscape 1*and the varnished lower section of *Landscape 2*. These zones were selected because any dissolved pigment left on the swab would be easy to see. Each area was divided into six equal segments, outlined with white chalk dashed lines (Fig. 11 and 12). The upper three segments were treated by dabbing with solvent-moistened cotton swabs—applying identical pressure at each point—while the lower three segments were treated by rolling the swab across the surface. The six segments were tested from left to right with the following solvents: GVR, TACO2, and a 1 : 1 : 1 blend of DMSO–MEK–acetone.

Figure 11. Test 1 on Landscape 1 (aged varnish). White dashes on the tree marked the test area. Treatments: left (GVR), middle (TACO2), right (DMSO–MEK–acetone 1:1:1).

Figure 12. Test 1 on Landscape 2 (fresh varnish). White dashes on the lower varnished section marked the test area. Treatments: left (GVR), middle (TACO2), right (DMSO–MEK–acetone 1:1:1).

2.4 Solubility Test 2– Comparing swabs and Japanese tissues

Because solvents contain different volatile components, 20 g of Japanese tissue was applied to the varnish and sealed under plastic wrap to extend the contact time with the varnish layer. This procedure enabled the comparison of reaction efficiency between conventional solvents and GVR under identical exposure conditions.

On *Landscape 1*'s sky area and Landscape 2's grass area—both uniformly colored. Eight 3 × 3 cm squares were marked in each region with solid white lines (Figs. 13 and 14).

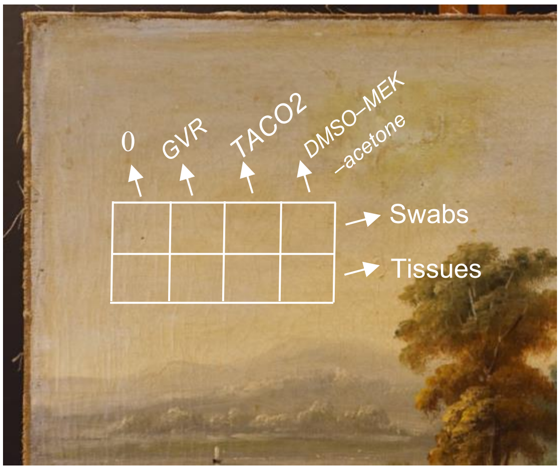


Figure 13. Landscape 1 before treatment

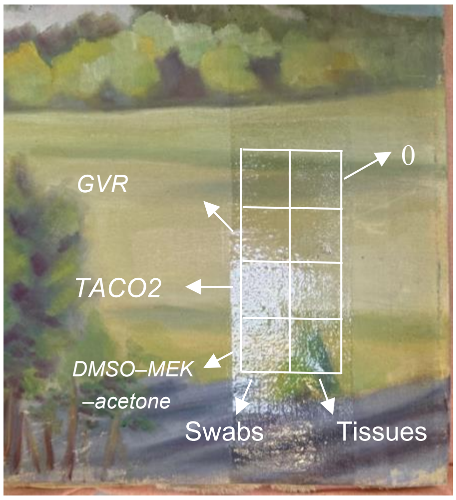


Figure 14. Landscape 2 before treatment

Square "0" was designated as the untreated control. The upper half of each square was treated by rolling and wiping with cotton swabs soaked at both ends in the test solvent. The lower half was covered with the pre-soaked Japanese tissue and wrapped in plastic for 90 seconds without any mechanical action. Squares 4–6 were assigned as follows: GVR, TACO2, and DMSO blend (1 : 1 : 1). The swabs and tissues were then removed to reveal the varnish response.

2.5 Evaporation Rate Test- Gravimetric Method

Volatility was assessed by measuring changes in mass and volume before and after exposure. For each test, 6 mL of solvent was placed in an measuring cylinder and weighed (Fig. 15). The beakers were left open to the air for a fixed period. After exposure in air, the remaining solvent's mass and volume were recorded. A greater decrease in mass and volume indicated higher volatility. This procedure provided quantitative volatility values for all three solvent formulations.

Figure 15. Weigh one of the solvent cylinders.

2.6 Identify residual aged varnish after treatment.

Old varnish undergoes oxidative aging after long-term exposure to UV light, and it develops molecular structures that absorb ultraviolet radiation and emit visible fluorescence. Using UV illumination thus helps identify residual aged varnish on a painting's surface (Taft et al., 2000, p.75).

2.7 X-ray fluorescence (XRF) test

The XRF test is used to identify pigment elements. X-radiation is absorbed by high-density electrons. Since metals contain many electrons, X-rays can be used to identify metallic elements present in mineral pigments, such as white lead (Taft et al., 2000, pp. 79–80).

First, the uncleaned paint surface was measured to record its baseline metal content. After cleaning, cotton swabs and Japanese tissue were analyzed: the presence of the same metal peaks indicated that pigment had been dissolved and the paint layer damaged, although surface dirt or airborne particles could also account for these signals. Measurement settings were: 40 s, 40 kV, 20 µA.

Blank swabs and paper were tested to confirm that no metals were introduced by the materials. Peak comparisons were performed using the PyMCA software.

In Solubility Test 2, swabs from the sky area of *Landscape 1* and the grass area of *Landscape 2*, along with 20 g of Japanese tissue (Fig. 16), were collected for X-ray fluorescence (XRF) analysis. The aim was to identify whether the same pigment elements found in the original paint surfaces were also present on the swabs and tissue after treatment, which would indicate pigment dissolution.

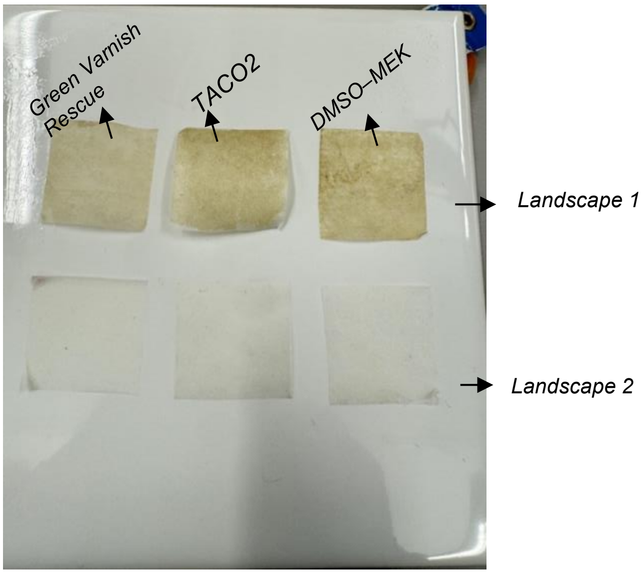


Figure 16. Tissues used after varnish removal. The top row is from Landscape 1, and the bottom row is from Landscape 2.

Additionally, the swab used on the roof area in Solubility Test 1 was retained for XRF testing, as pigment loss was suspected during cleaning.

All swabs were tested while held in place with a clamp (Fig. 17). Their elemental peaks were compared with clean swabs and the corresponding painting surfaces. The 20 g Japanese tissue was tested in two configurations: laid flat on a ceramic tile and folded three times, then clamped in the air. Elemental peaks were compared with clean tile and the painting surface.

Figure 17. The swab was held aloft by a clamp, and the red detection focal point of the XRF test is aimed at the varnish residue on the swabs.

2.8 Use of AI-assisted Language Tools

During the writing process, AI language models (DeepSeek-) were employed exclusively for text polishing and improving contextual coherence. The tool assisted in rephrasing sentences for clarity and logical flow, but all experimental data, analysis, conclusions, and academic integrity remain solely the author's original work.

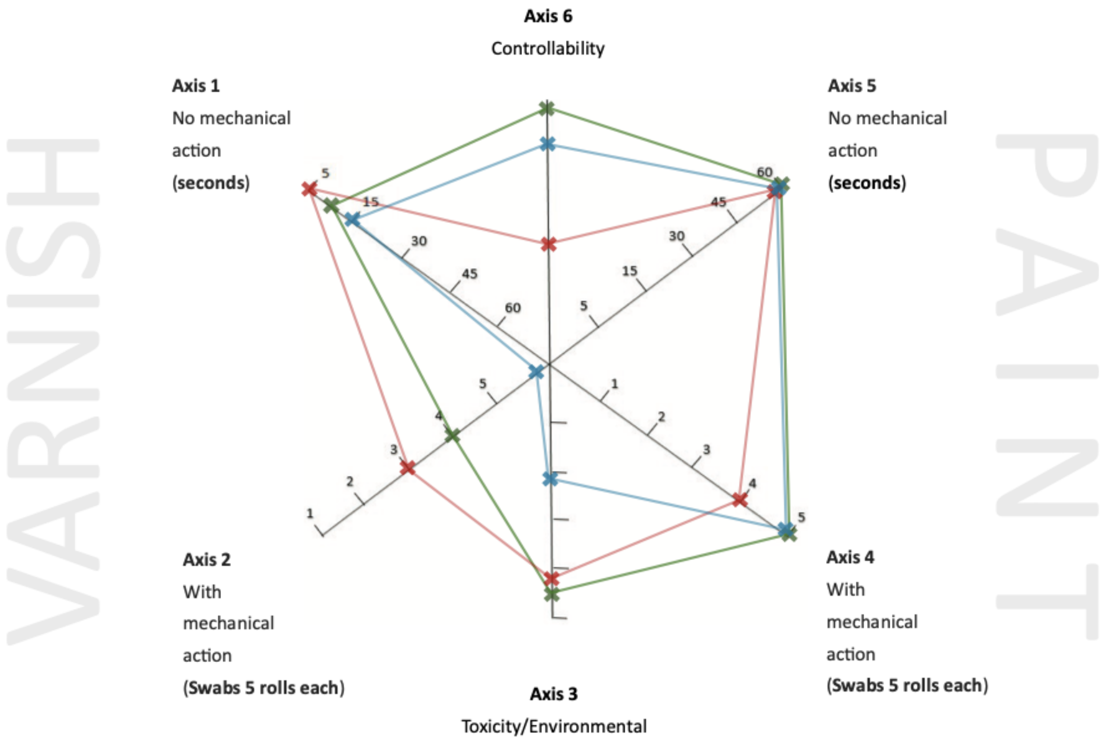
3 RESULTS

3.1 Solubility test 1

The three solvents were assigned the following colors for all the Fife Solvent Star charts: GVR in green, TACO2 in blue, and the DMSO blend in red. In the recorded results for *Landscape 1* (Tab. 2), the green area is the largest, indicating that GVR achieved the most effective removal of the aged varnish. The toxicity value is based on the CHEM21 rating table (Fife, 2021, p.42), which is relative.

Table 2. The Fife Solvent Star charts for *Landscape 1*

Painting Description: Oil painting on panel, signed, 19th-20th century, 34 x 46 cm
Title: *Landscape 1*(Aged varnish)
Artist: Unknown



Solvent	Ratio (if mixture)	Color Legend	Quantity solvent (mi)	
			spot A	spot B
Green Rescue	unknown	green	0.1	0.1
TACO2(isopropanol–n-octane–acetone blend)	15% : 46% :39%	blue	0.1	0.1
DMSO-MEK-acetone	1:1:1	red	0.1	0.1

Date of testing: 2025-4-13
Notes/comments: Aged varnish. Pigment dissolution was observed upon the fourth rolling pass of the swab with DMSO-MEK-acetone solvent.
Selected Solvent/Approach: Green Rescue

The experimental results for *Landscape 1* are summarized as follows:

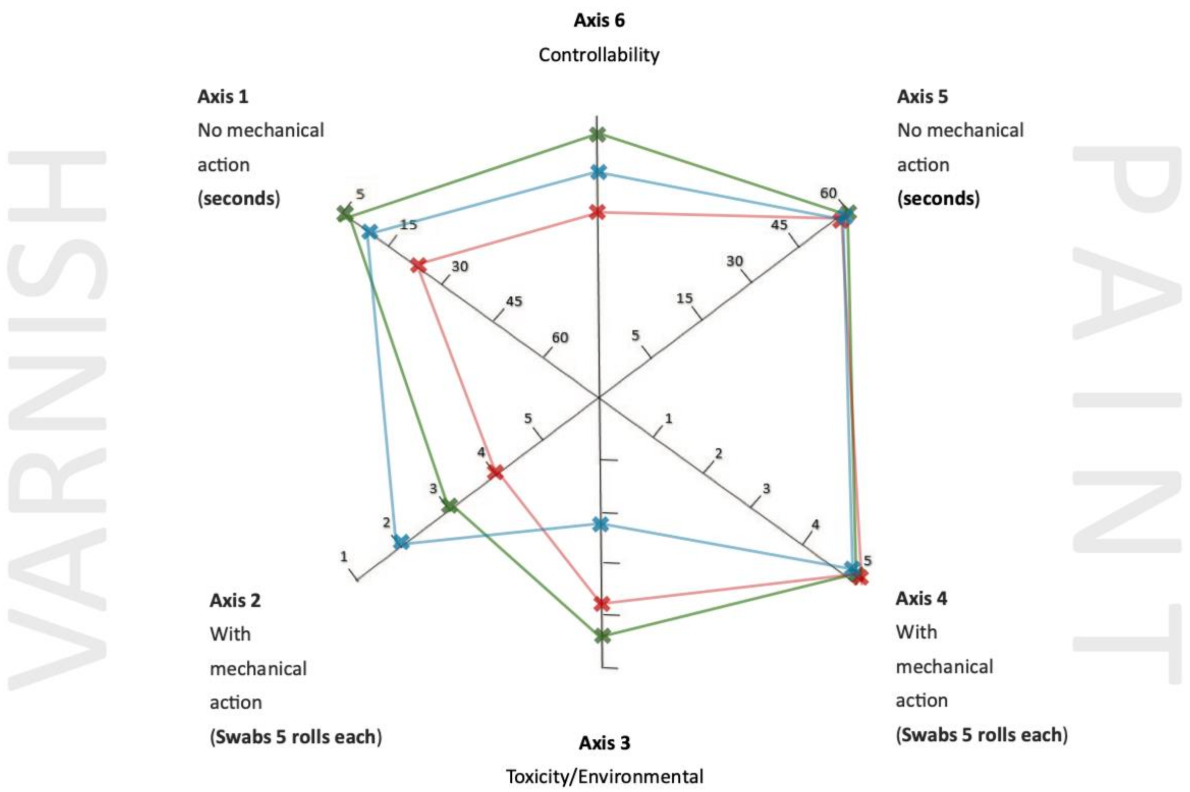
- GVR
  Fast varnish removal and easy to control.
- TACO2
  Evaporates quickly but it reacts slowly and shows low cleaning efficiency.
- DMSO-MEK–acetone blend (1:1:1)
  Dissolved varnish too quickly and is difficult to control. In the roof area of the house, pigment loss was observed during the fourth swab roll, where a brown paint layer was removed (Fig. 18).

Figure 18: By the fifth swipe of the swab, the brown pigment from the eave area had visibly dissolved onto the swab.

In the Fife Solvent Star chart results for *Landscape 2* (Tab. 3), the green area is again the largest, indicating that GVR was the most effective solvent for removing the fresh varnish layer.

Table 3. The Fife Solvent Star charts for *Landscape 2*

Painting Description: Oil painting on duk, signed, 1914, 58X39cm
Title: *Landscape 2* (new varnish)
Artist: Urho Alex Zacharov



Solvent	Ratio (if mixture)	Color Legend	Quantity solvent (mi)	
			spot A	spot B
Green Rescue	unknown	green	0.1	0.1
TACO2(isopropanol–n-octane–acetone blend)	15% : 46% :39%	blue	0.1	0.1
DMSO-MEK-acetone	1:1:1	red	0.1	0.1

Date of testing: 2025-4-13
Notes/comments: DMSO-MEK-acetone has poor solubility, and blooming was found 30 minutes after treatment. TACO2 and Green Rescue have good effects.
Selected Solvent/Approach: Green Rescue

Table 4. Solvents performance comparison.

Solvent	GVR	TACO2	DMSO blend
Performance on Landscape 2 (Fresh Varnish)	Fastest removal, easy to control.	Moderate cleaning performance	Slowest removal; caused white blanching
Performance on Landscape 1 (Aged Varnish)	Consistently high efficiency	Less effective than on fresh varnish	Overly aggressive. A white blanching effect was observed in the test area after 30 minutes.risk of pigment damage
Key Observations	Low volatility/odor, easy handling; safe for both fresh and aged varnish.	Works better on fresh synthetic varnish; weaker on aged layers.	Poor cleaning on fresh varnish; hazardous for aged varnish due to excessive action

After applying the DMSO blend with a swab with no mechanical action to the purple area of the painting, blooming was observed after 30 minutes (Fig. 19). No blooming appeared in the area where the swab was rolled, and no blooming was observed after cleaning with the other solvents.

Figure 19. The white area indicated by the red arrow shows blooming.

3.2 Solubility test 2

Solubility Test 2 compares the cleaning performance of cotton swabs versus Japanese tissue 20g on both the fresh and aged varnish of *Landscape 1* and *Landscape 2* (Figs. 20 and 21).

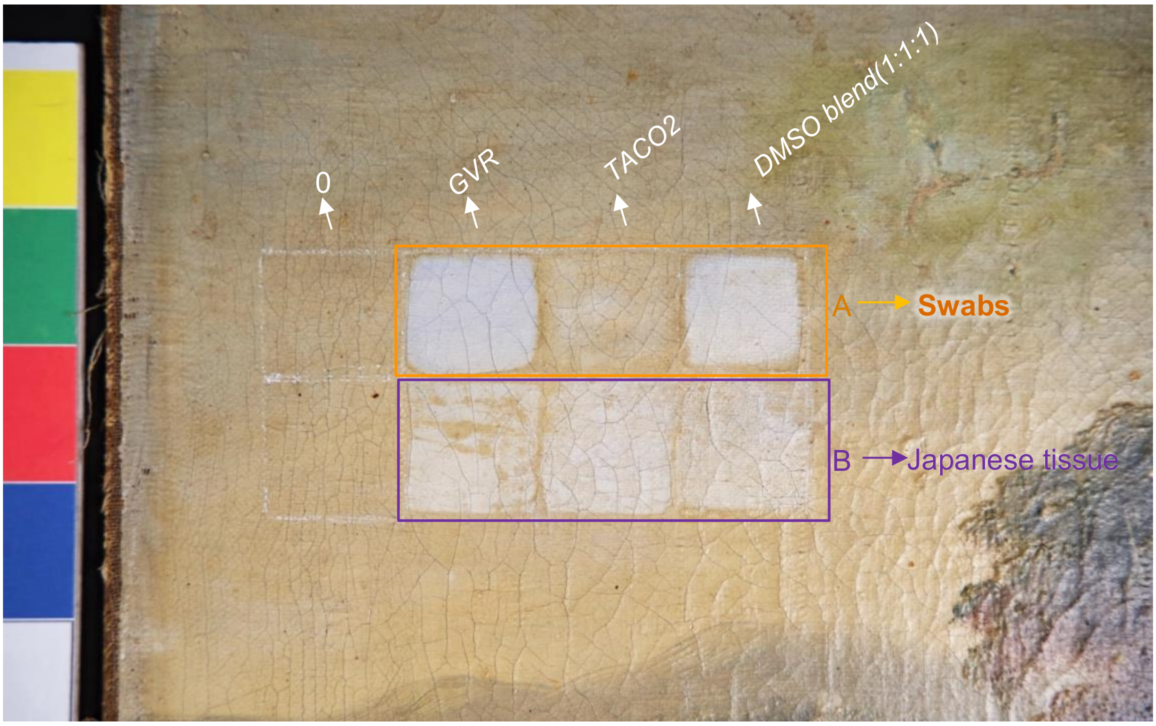


Figure 20. Landscape 1 after cleaning.

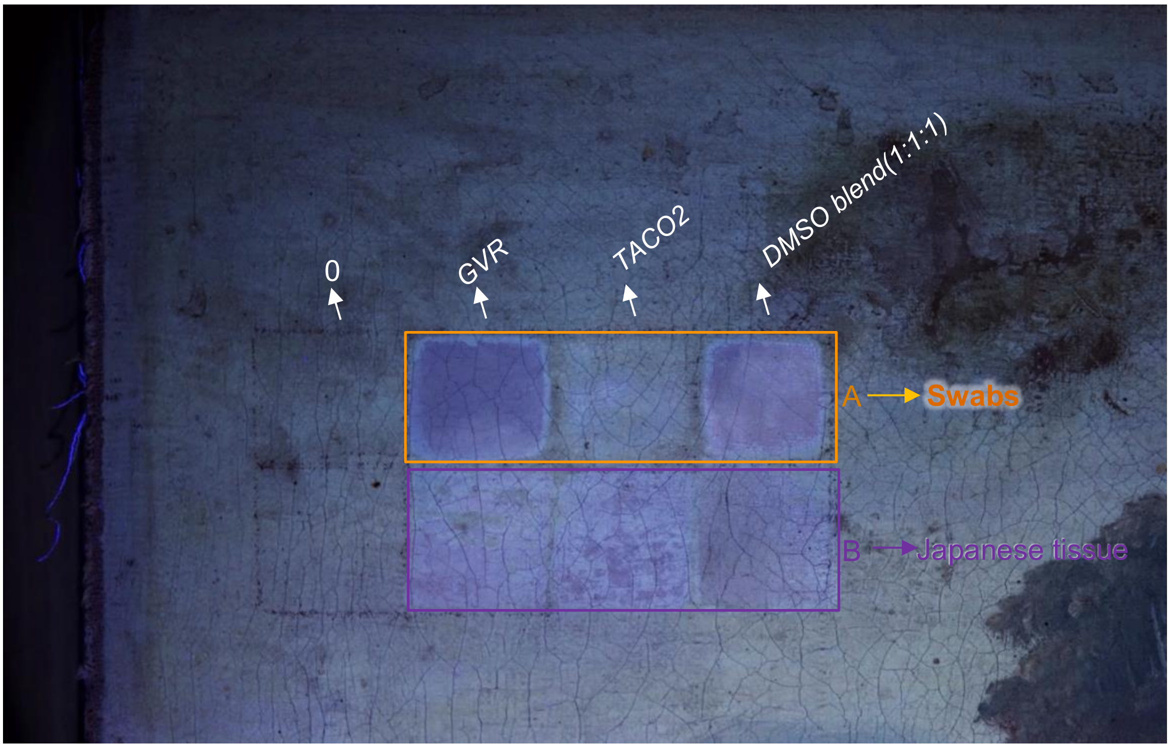


Figure 21. UV light photograph of Landscape 1 after cleaning.

Orange boxes cleaned with cotton swabs; Purple boxes cleaned with Japanese tissue. From left to right were the reference sample, GVR, TACO2, and DMSO(1:1:1).
Under UV illumination (Fig. 21), deeper purple fluorescence indicates more complete varnish removal. When combined with the visible-light image (Fig 20) and the UV photograph, the *Landscape 1* cleaning results are summarized in Tab. 3.

Table 5. Results of Solubility Test 2 on *Landscape 1* (aged varnish)

Landscape 1	Material	GVR	TACO2	DMSO blend (1 : 1 : 1)
A	Swabs (orange)	Good – mechanical action improves efficiency	Poor – fast evaporation limits swelling	Moderate – less effective than GVR
B	Japanese tissue (purple)	Mediocre – performed poorly in areas where the tissue lifted and failed to make proper contact.	Mediocre – slightly better than GVR	Poor – tissue sticks to the surface, uneven removal

Observations – **Aged** Varnish (*Landscape 1*) after treatment:

- **GVR** + swab, mechanical action → aged varnish: Gave the best cleaning result. The varnish required over five seconds to begin swelling, after which it could be removed with the same swab.
- **TACO2** + swab, mechanical action → aged varnish: Evaporated too quickly; the swab dried before the varnish could swell across the test area.
- **DMSO–MEK–acetone(1:1:1)** + swab, mechanical action → aged varnish: Moderate cleaning; some yellowed varnish residues remained.
- **GVR** + Japanese tissue, no mechanical action → aged varnish: Varnish absorbed by the tissue.
- **TACO2** + Japanese tissue, no mechanical action → aged varnish**:** Cleaning was more effective and even than with swabbing.
- **DMSO–MEK–acetone (1:1:1)** + Japanese tissue, no mechanical action → aged varnish: Varnish swelled into a sticky gel and adhered to the surface; removal was incomplete and left residues behind.

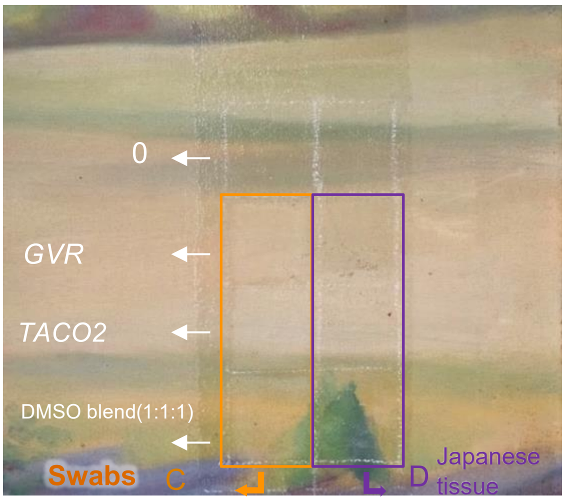


Figure 22. Landscape 2 after cleaning.

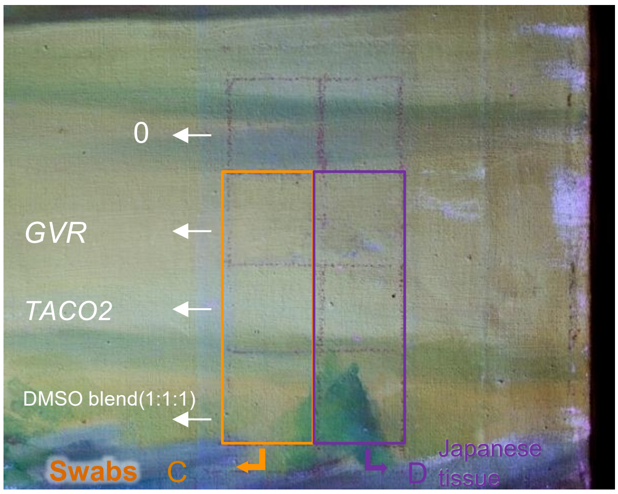


Figure 23. UV light photo of Landscape 2 after cleaning.

Under UV illumination, the fresh varnish layer appears light blue (Fig. 23). Neither the visible-light nor the UV photographs clearly demonstrate the varnish removal effectiveness (Figs. 22, 23). The following observations are a summary of recorded cleaning results (Tab. 6) for Landscape 2 (fresh varnish).

Table 6. Results of Solubility Test 2 on *Landscape 2* (fresh varnish)

Landscape 1(fresh varnish)	Material	GVR	TACO2	DMSO blend (1 : 1 : 1)
C	Swabs(orange)	Good	Mediocre	Mediocre
D	Japanese tissue(purpure)	Good	Mediocre	Poor

Observations – **fresh**Varnish (*Landscape 2*) After Treatment:

- **GVR** + swab mechanical action → **fresh** varnish: very clean, best result, no varnish residue.
- **TACO2** + swab mechanical action → **fresh** varnish: moderate result, no varnish residue.
- **DMSO–MEK–acetone (1:1:1)** + swab mechanical action → **fresh** varnish: moderate result, varnish residue remained in the center.
- **GVR** + Japanese tissue, no mechanical action → **fresh** varnish: moderate result, slight residue on the right side.
- **TACO2** + Japanese tissue, no mechanical action → **fresh** varnish: moderate result, slight residue on the left side.
- **DMSO–MEK–acetone (1:1:1)** + Japanese tissue no mechanical action → **fresh** varnish: the most varnish residue remained.x

3.3 Evaporation Rate Tests

All weights include the graduated cylinder. Measurements were taken hourly for the first six hours, and again at 24 h, 120 h, and 312 h; data between hours 3 and 6 are omitted for brevity (Tab.7).

Table 7. Weight and volume changes of the three solvents at fixed time intervals.

Solvent	Remaining	Initial	1h	2h	24h	120h	312h
GVR	Weight (g)	37.171	37.149	37.135	37.099	36.003	35.222
TACO2		36.455	36.411	36.384	36.319	34.166	33.235
DMSO blend		37.506	37.426	37.426	37.356	35.563	34.610
GVR	Volume (ml)	6	6	6	6	4.8	4.4
TACO2		6	5.9	5.9	5.8	3	1.8
DMSO blend		6	5.8	5.8	5.8	3.5	2.3

- GVR's weight decreased by 1.949 g and its volume decreased by 1.6 ml over 312 hours.
- TACO2's weight decreased by 3.220 g and its volume decreased by 4.2 ml over 312 hours.
- The DMSO blendsaw a weight decreased by 2.896 g and a volume decreased by 3.7 ml over 312 hours.

After 312 hours of evaporation, using the same starting volume of 6 mL, the remaining liquid shown in Figure 24 clearly indicates that TACO2 (measuring cylinder No. 2) had the lowest residue, while GVR (cylinder No. 1) retained the most (Fig. 24).

Figure 24. Remaining amounts of the three solvents after 13 days of evaporation, from left to right: GVR, TACO2, and DMSO blend.

The comparison of evaporation rates is summarized as follows:

- **GVR:** Lowest evaporation rate
- **TACO2:** Highest evaporation rate
- **DMSO blend:** Moderate evaporation rate

3.4 X-ray fluorescence (XRF) analysis to Assess Residual Pigments After Cleaning

X-ray fluorescence (XRF) analysis determines whether pigments have been dissolved by comparing the residual substances after cleaning with the metal elements in the color layer.

3.4.1 GVR X-ray fluorescence (XRF) result

No pigment residues were detected on the swabs or tissues after cleaning both the old and fresh varnish. For the surface of the sky in *Landscape 1*, after cleaning, the point marked in red (Fig. 25) was selected for X-ray fluorescence (XRF) testing.

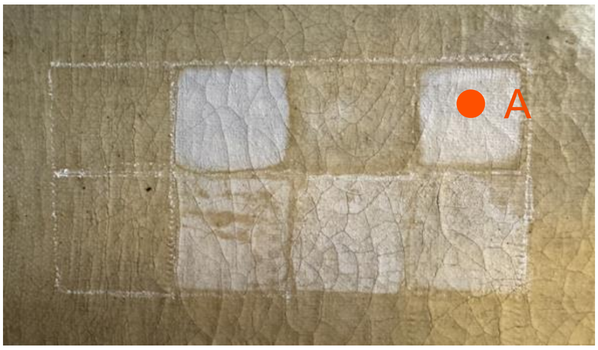
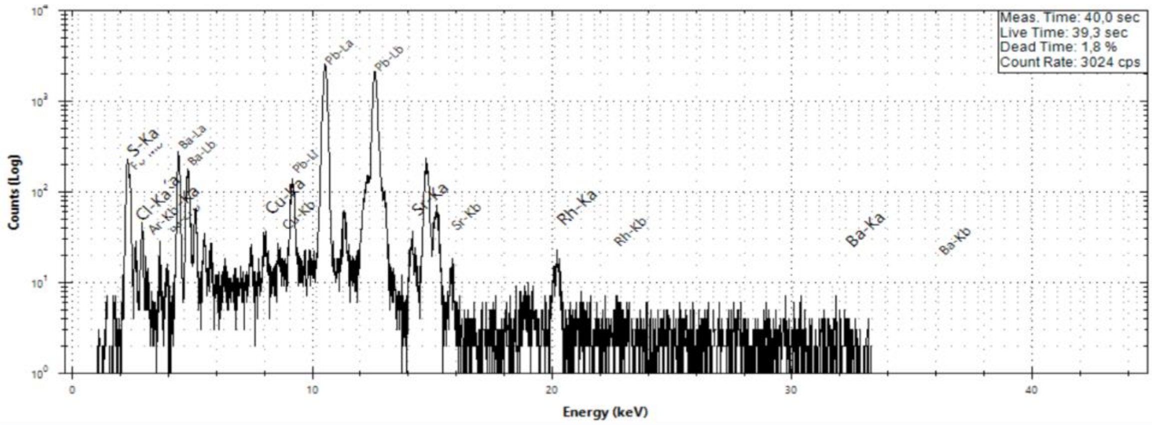


Figure 25. The red dot A marks the location of X-ray fluorescence (XRF) testing on the sky area of the painting's surface after cleaning.

Since it had already been cleaned with the strongest solvent, it was unlikely to retain stains or airborne pollutants. The test report is shown in Fig. 25.



Analysis Results:

Element	Concentration	Error
S	55,67%	±2,95%
Pb	36,03%	±0,48%
Ba	5,85%	±1,86%
~~Cl~~	~~1,37%~~	~~±10,06%~~
~~Ca~~	~~0,71%~~	~~±13,23%~~
~~Sr~~	~~0,23%~~	~~±4,57%~~
~~Cu~~	~~0,13%~~	~~±6,1%~~

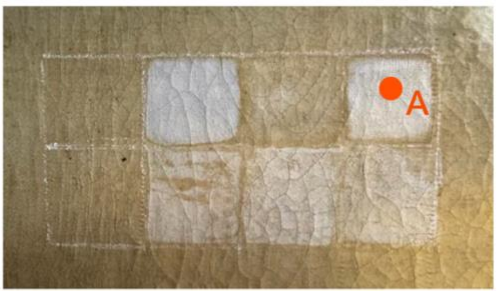
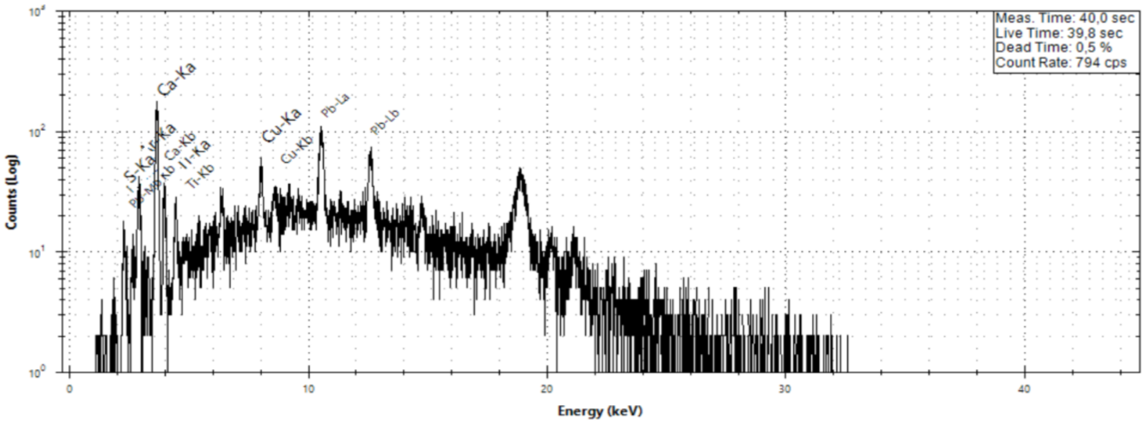


Figure 26. XRF analysis report of the red dot A in the painting's sky area surface. Foto:Bruker.

The sky pigment report (Fig. 26) indicates the presence of Pb and Ba elements in the sky area pigments of the oil painting, likely corresponding to Lead White pigment and Barium Sulfate in the ground layer. The elements of Cl, Ca, Sr, Cu, and Ti in the two reports were below the error value, so they were marked out. This marking will also be used to indicate this in subsequent reports.



Analysis Results:

Element	Concentration	Error
Ca	50,74%	±2,6%
S	41,89%	±7,99%
Pb	3,69%	±2,86%
~~Ti~~	~~2,84%~~	~~±7,44%~~
~~Cu~~	~~0,84%~~	~~±5,28%~~

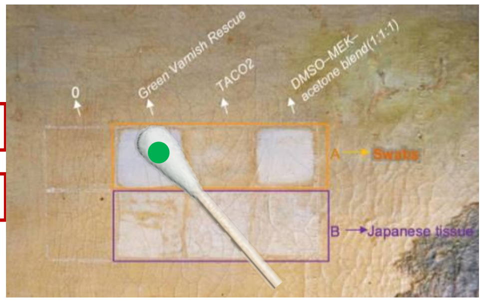


Figure 27. The XRF analysis report after cleaning with GVR using a swab (green dot). Foto:Bruker.

The Ca element come from the clean swabs. The Swab report (Fig. 27) shows minimal residual Pb elements on the swab. When comparing the overlaid spectra in Fig. 28, a slightly elevated peak appears in the 10-13 keV range (marked in blue), but this minor deviation is negligible. Thus, it can be concluded that GVR, used a swab, did not dissolve or damage the paint layer.

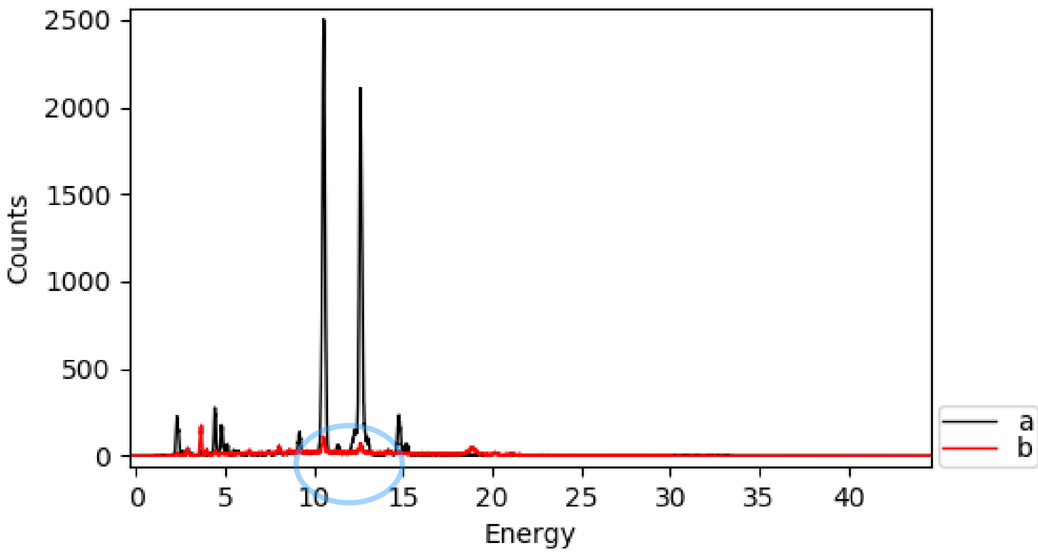
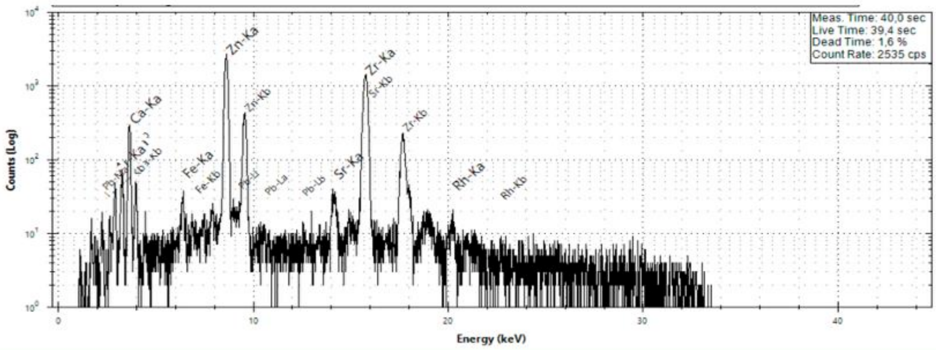


Figure 28. The black peaks represent the Pb and Ba elemental signatures detected in the sky area pigments of the oil painting; the red peaks show the elemental signatures obtained from the swab with GVR analysis. Foto:PyMca

The Japanese tissue, due to its thin nature, was placed on a ceramic plate for X-ray fluorescence (XRF) testing (Fig. 29).

Figure 29. The upper three tissue samples display residues deposited on a ceramic plate after cleaning aged varnish with three solvents, whereas the lower three show residues collected when cleaning fresh varnish with the same solvents.

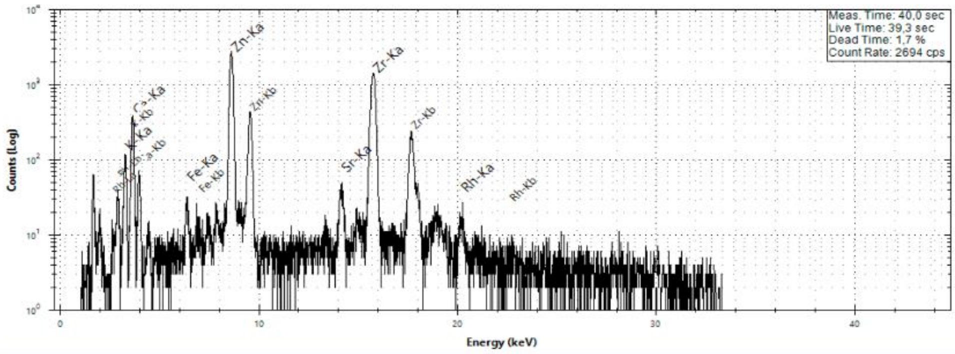
The X-ray fluorescence (XRF) analysis report of the tissue sample (Fig. 30) and the clean ceramic plate (control) (Fig. 31) were compared, and the same metal elements were present, with no other metals dissolved out. Therefore, no pigments were dissolved after cleaning aged varnish with Japanese tissue and GVR.



Analysis Results:

Element	Concentration	Error
Ca	37,95%	±1,8%
Zn	24,25%	±0,51%
Zr	20,61%	±0,59%
K	10,79%	±3,91%
Pb	5,75%	±6,91%
Sr	0,34%	±3,92%
Fe	0,31%	±6%

Figure 30. XRF report of the Japanese tissue cleaned with GVR on Landscape 1(green dot). Foto:Bruker.



Analysis Results:

Element	Concentration	Error
Ca	43,07%	±1,74%
Zn	24,77%	±0,53%
Zr	16,94%	±0,62%
K	14,59%	±3,21%
Sr	0,32%	±4,38%
Fe	0,31%	±6,36%

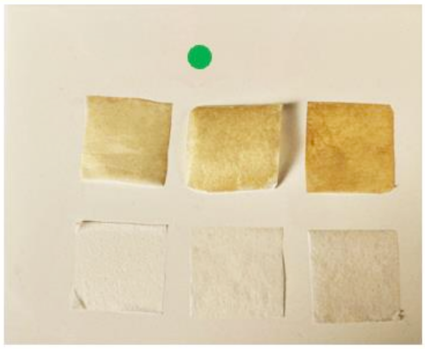
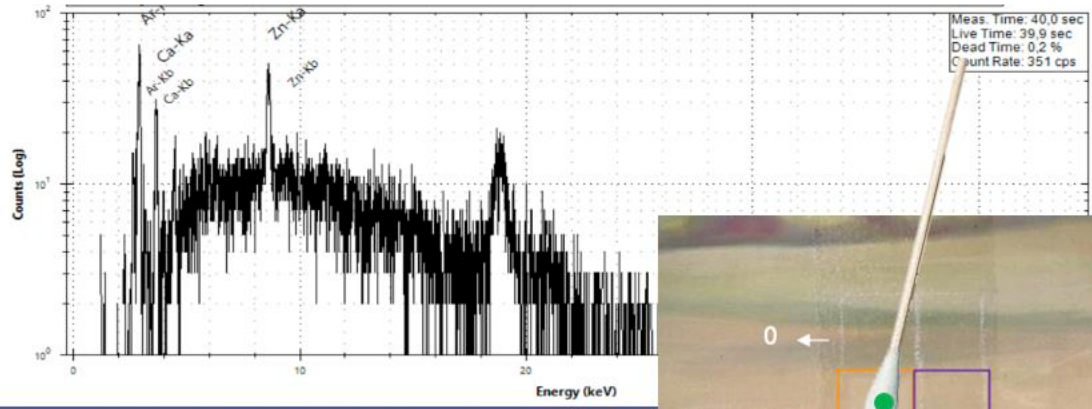


Figure 31. XRF report of the clean ceramic plate (control, green dot). Foto:Bruker.

GVR was applied using both a swab and Japanese tissue to clean fresh varnish on Landscape 2. The following is the X-ray fluorescence report on the swab (green dot in Fig.32) and Japanese tissue (green dot in Fig.33).



Analysis Results:

Element	Concentration	Error
Ca	81,68%	±6,32%
Zn	18,32%	±4,55%

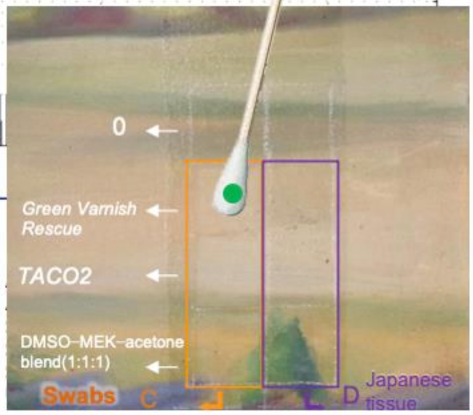
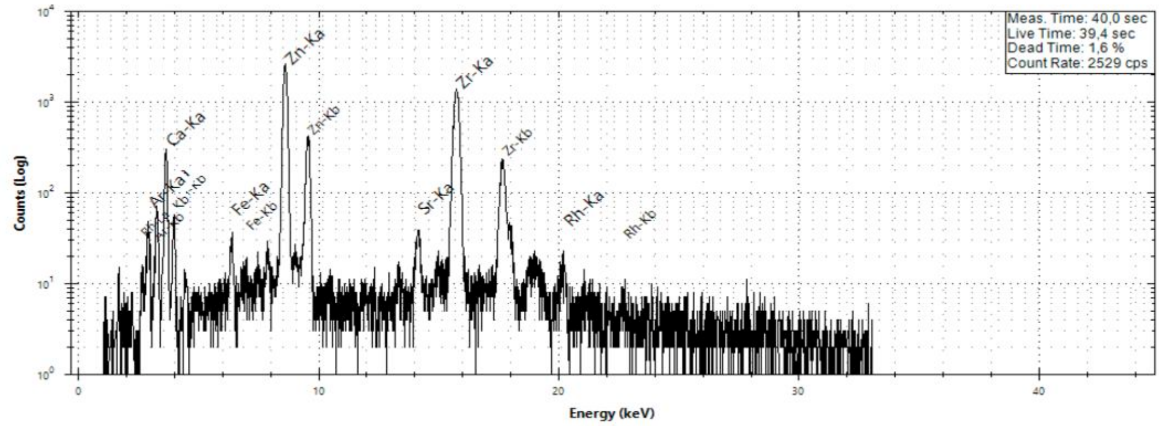


Figure 32. X-ray fluorescence report of swab (green dot) with GVR after cleaning the Landscape 2- fresh varnish. Foto:Bruker.



Analysis Results:

Element	Concentration	Error
Ca	39,59%	±1,94%
Zn	27,88%	±0,55%
Zr	21,43%	±0,64%
K	10,43%	±4,41%
~~Sr~~	~~0,36%~~	~~±4,7%~~
~~Fe~~	~~0,31%~~	~~±6,83%~~

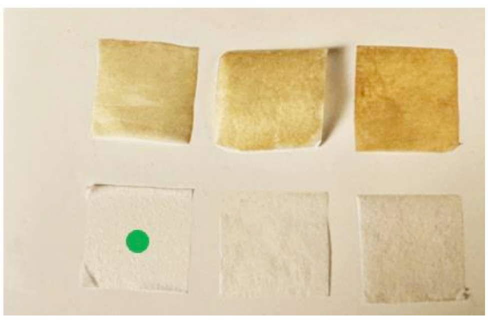
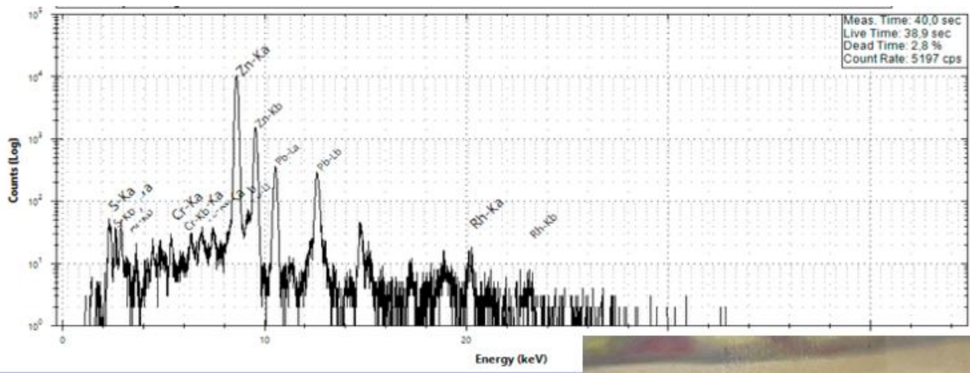


Figure 33. X-ray fluorescence report of tissue with GVR after cleaning the Landscape 2- fresh varnish. Foto:Bruker.

The grass area of *Landscape 2* was detected Zn and Pb elements (Fig. 34).



Analysis Results:

Element	Concentration	Error
Zn	63,03%	±0,26%
S	17,52%	±6,73%
Cl	10,59%	±6,77%
Pb	8,51%	±1,37%
Cr	0,14%	±7,84%
Ni	0,11%	±3,67%
Fe	0,1%	±7,2%

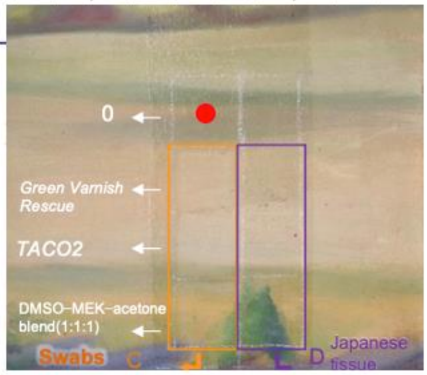


Figure 34. X-ray fluorescence report of Landscape 2's grass area. Foto:Bruker.

Although trace Zn was detected in the tissue (Fig. 35, blue peak), its peak profile matched the control measurement from the clean ceramic plate (Fig.35, black peak), demonstrating that the tissue cleaning method did not extract significant amounts of pigment from the artwork.

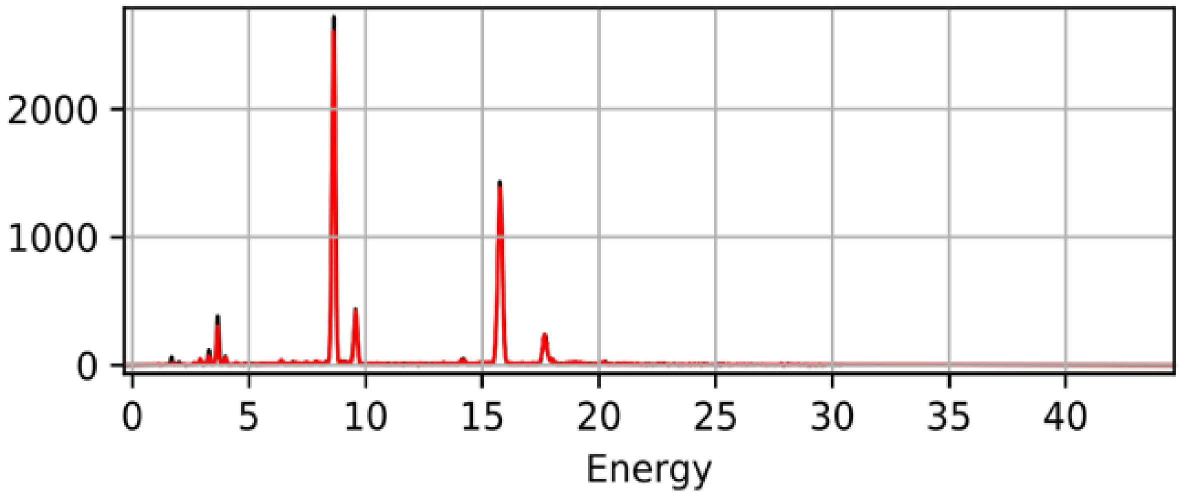


Figure 35. Comparative XRF analysis of elemental peaks: the black peak represents the clean ceramic plate, while the red peak corresponds to the tissue treated with GVR. Foto: PyMca.

Although trace Zn was detected in the swab used with GVR (Fig. 36, red peak), the peak intensity was negligible compared to that of the grassy area in *Landscape 2* (Fig.36, black peak), demonstrating that the swab cleaning method did not extract significant amounts of pigment from the artwork.

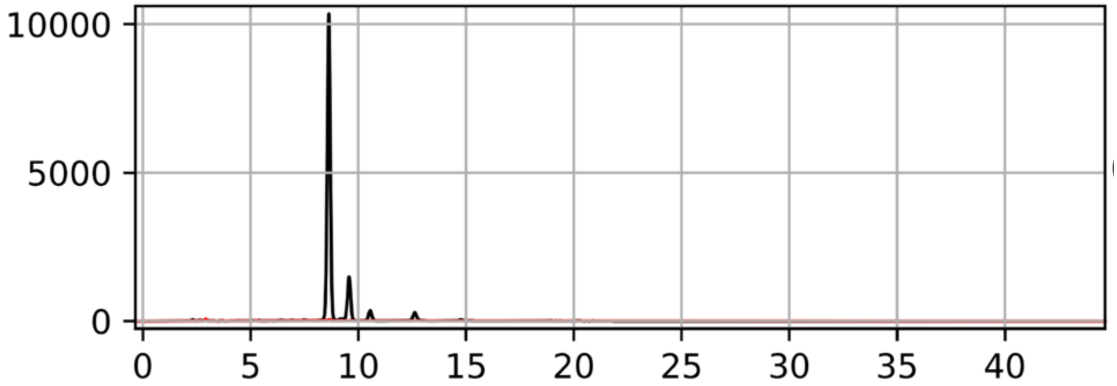
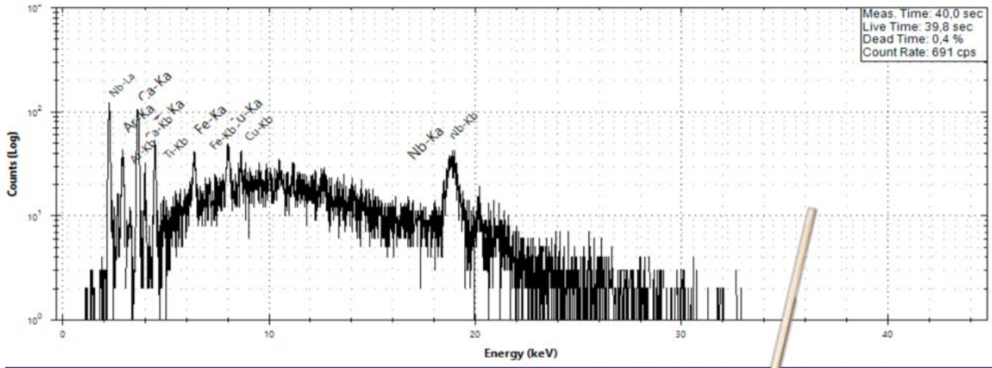


Figure 36. The metal peaks from the grass area of Landscape 2 (black), those from the swab(red) used with the GVR after cleaning. Foto: PyMca.

3.4.2 TACO2 X-ray fluorescence (XRF) result

- *Landscape 1* aged varnish



Analysis Results:

Element	Concentration	Error
Ca	67,95%	±3,08%
Ti	21,33%	±5,02%
Fe	6,1%	±5,32%
Cu	4,44%	±4,98%
Nb	0,18%	±3,61%

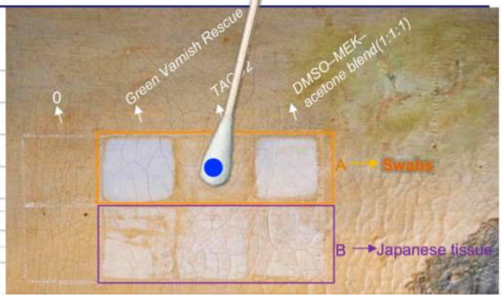
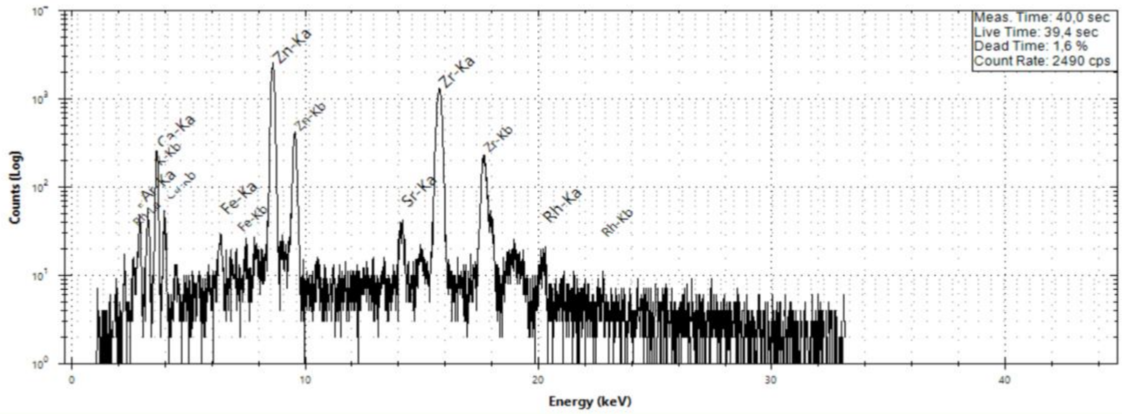


Figure 37. XRF report of swab with TACO2 after cleaning the Landscape 1. Foto:Bruker.

Ba and Pb were identified in the pigment layer of the *Landscape 1* sky, but neither element appeared in the peak (Fig. 37 and 38) from the swab or the tissue, indicating that TACO2 did not dissolve the aged varnish on *Landscape 1*.



Analysis Results:

Element	Concentration	Error
Ca	38,02%	±2,08%
Zn	29,18%	±0,55%
Zr	23,43%	±0,63%
K	8,53%	±5,09%
Sr	0,44%	±4,44%
Fe	0,4%	±6,15%

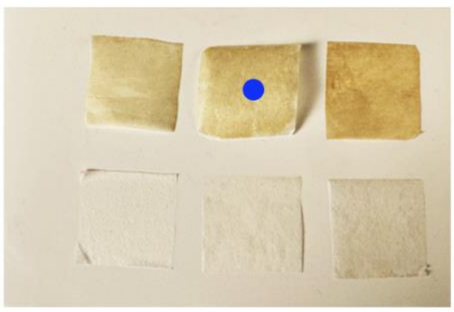
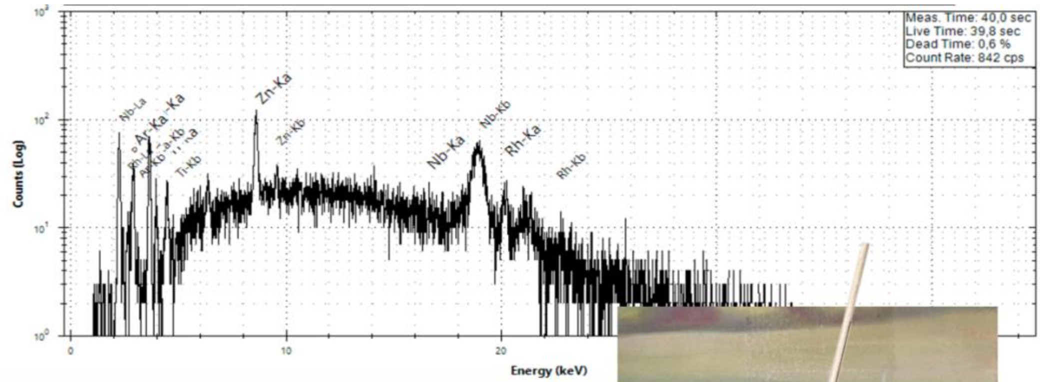


Figure 38.XRF report of tissue (blue dot) with TACO2 after cleaning the Landscape 1 aged varnish. Foto:Bruker.

– *Landscape 2* fresh varnish



Analysis Results:

Element	Concentration	Error
Ca	67,15%	±4,2%
Zn	16,69%	±2,91%
Ti	15,36%	±7,66%
Nb	0,8%	±4,22%

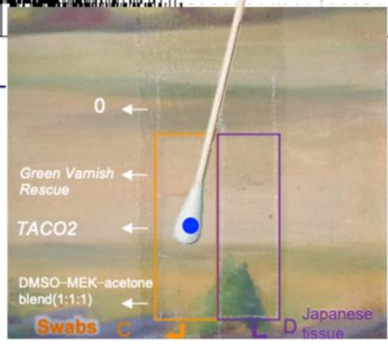
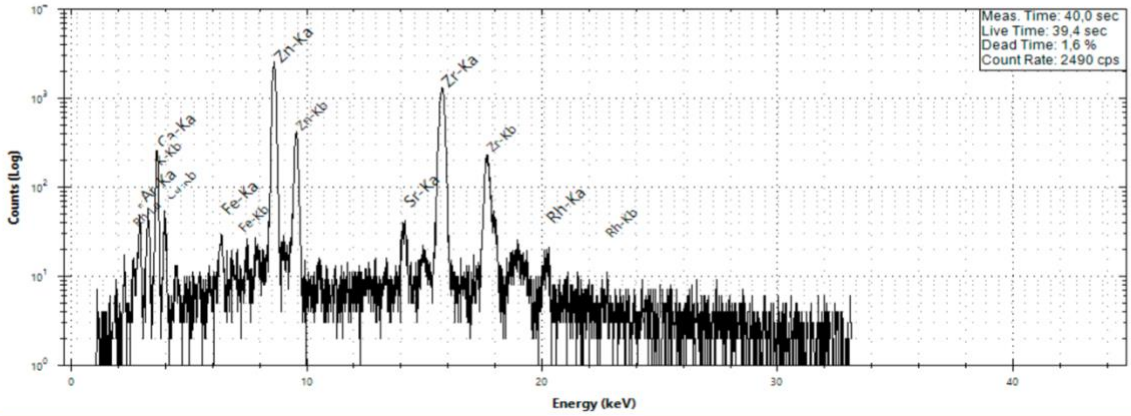


Figure 39. X-ray fluorescence report of swab (blue dot) with TACO2 after cleaning the Landscape 2 fresh varnish. Foto:Bruker.



Analysis Results:

Element	Concentration	Error
Ca	38,02%	±2,08%
Zn	29,18%	±0,55%
Zr	23,43%	±0,63%
K	8,53%	±5,09%
Sr	0,44%	±4,44%
Fe	0,4%	±6,15%

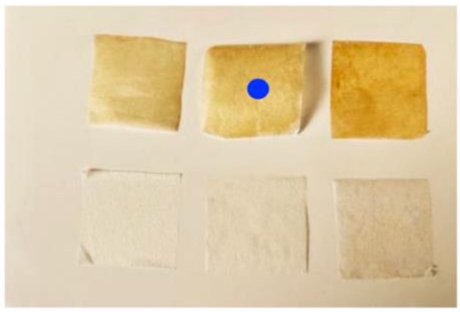


Figure 40. X-ray fluorescence report of tissue (blue dot) with TACO2 after cleaning the Landscape 2 fresh varnish. Foto:Bruker.

XRF analysis detected zinc (Zn) in both swab and tissue samples (Fig. 39 and 40).

While trace amounts of Zn were identified in the swab sample (Fig. 41, red peak), the peak intensity was negligible compared to that of the grassy area in Landscape 2 (Fig. 41, black peak), confirming that no substantial pigment dissolution occurred during the cleaning procedure.

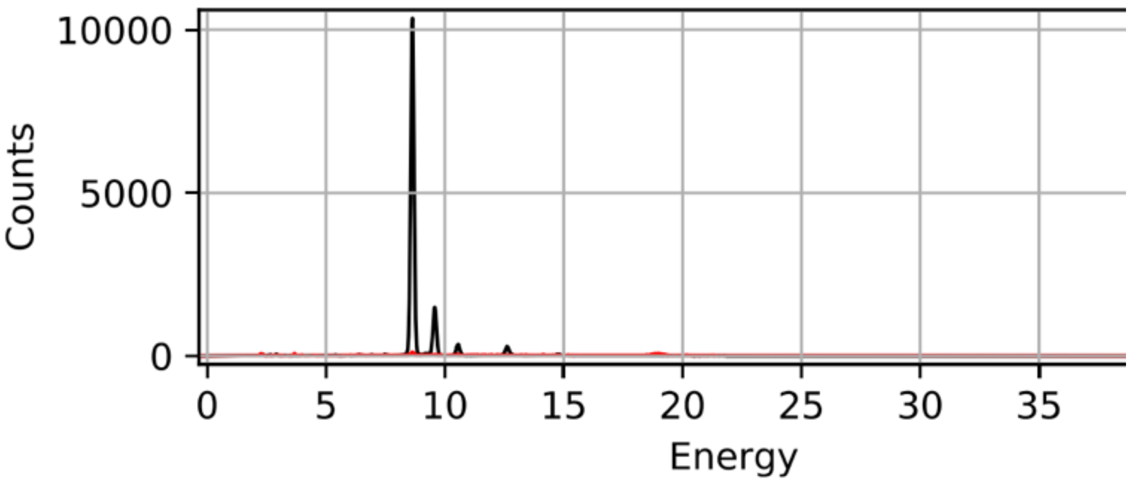


Figure 41. Comparative XRF analysis of zinc (Zn) elemental peaks: the black peak represents the grassy area in Landscape 2, while the red peak corresponds to the swab treated with TACO2 solvent. Foto: PyMca.

Although trace Zn was detected in the tissue (Fig. 42, blue peak), its spectral profile matched the control measurement from the clean ceramic plate (Fig. 42, black peak), demonstrating that the tissue cleaning method did not extract significant amounts of pigment from the artwork.

TACO2 neither dissolves the aged varnish on *Landscape 1*, nor the fresh varnish on *Landscape 2*.

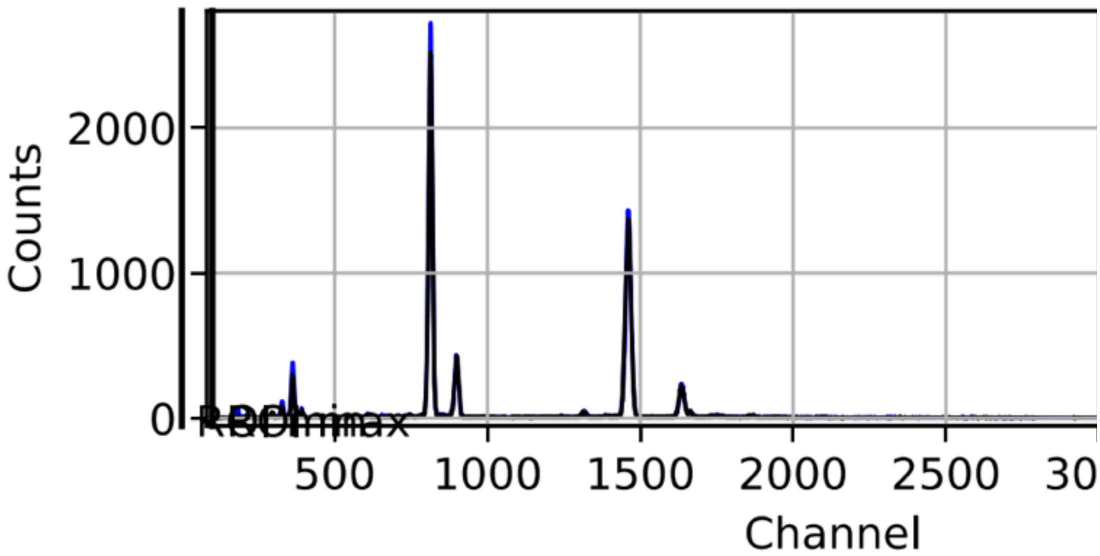
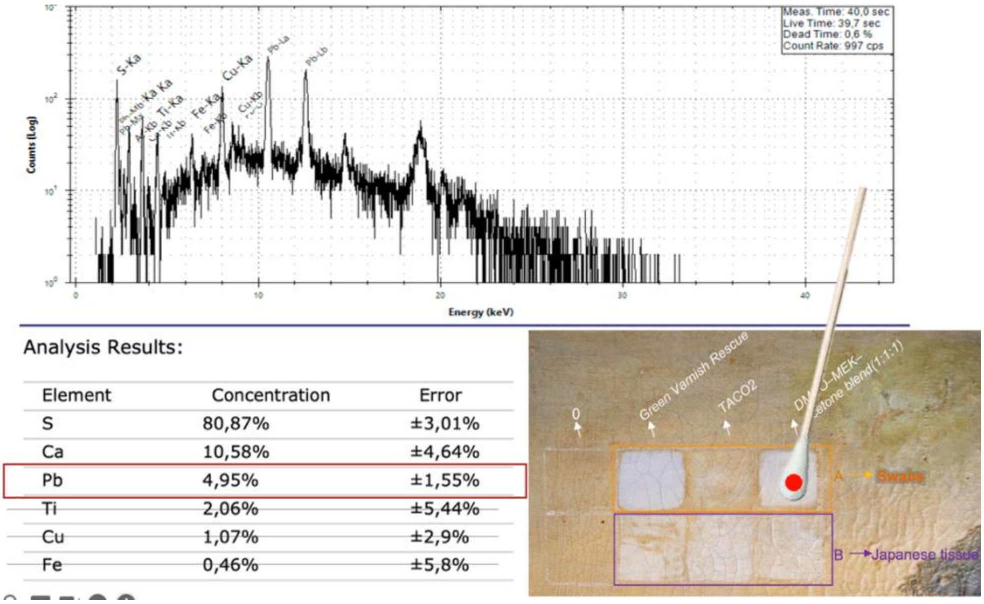


Figure 42. Comparative XRF analysis of zinc (Zn) elemental peaks: the black peak represents the clean ceramic plate, while the blue peak corresponds to the tissue treated with TACO2 solvent. Foto: PyMca.

3.4.3 DMSO blend X-ray fluorescence (XRF) result

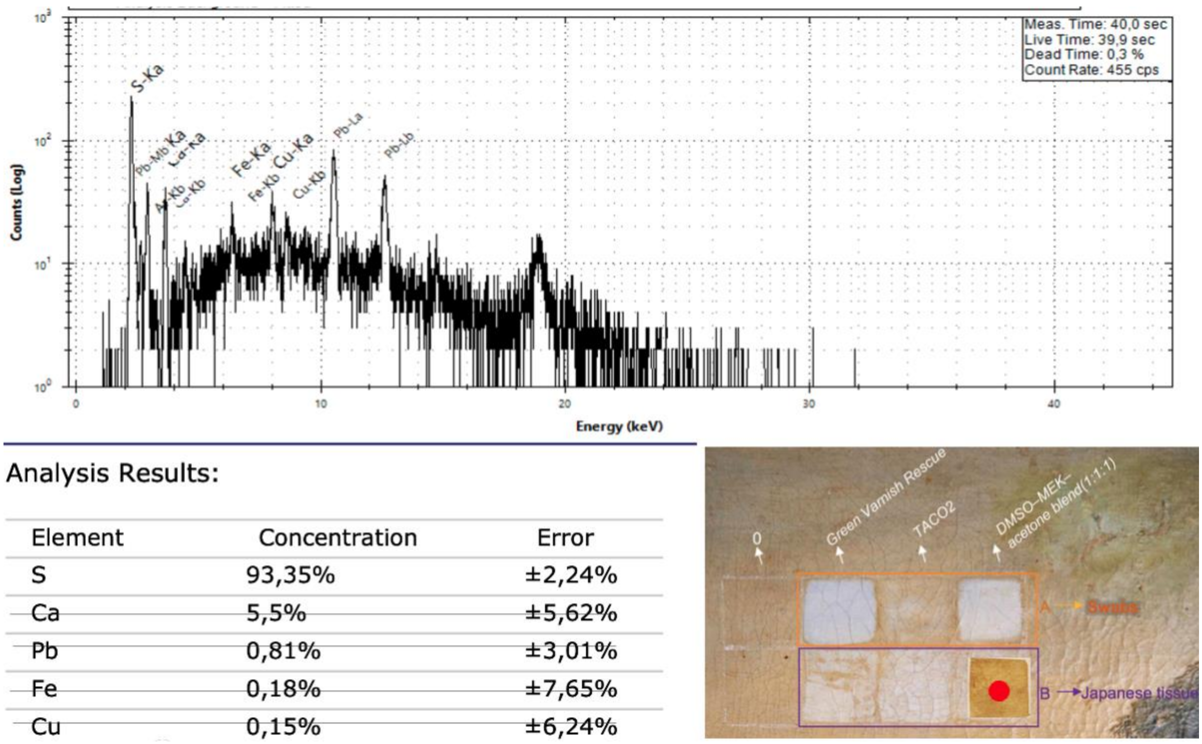
- *Landscape 1* aged varnish

Pb element was detected in the swab (Fig. 43) but not in the tissue (Fig. 44) after cleaning Landscape 1's aged varnish with DMSOblend.



Element	Concentration	Error
S	80,87%	±3,01%
Ca	10,58%	±4,64%
Pb	4,95%	±1,55%
Ti	2,06%	±5,44%
Cu	1,07%	±2,9%
Fe	0,46%	±5,8%

Figure 43. XRF report of swab (red dot) with DMSO blend after cleaning the Landscape 1 aged varnish. Foto:Bruker



Element	Concentration	Error
S	93,35%	±2,24%
Ca	5,5%	±5,62%
Pb	0,81%	±3,01%
Fe	0,18%	±7,65%
Cu	0,15%	±6,24%

Figure 44. XRF report of tissue (red dot) with DMSO blend after cleaning the Landscape 1 aged varnish. Foto:Bruker.

Although trace Pb element was detected in the swab used with DMSO blend (Fig. 45, red peak), the peak intensity was negligible compared to that of the sky area in *Landscape 1* (Fig.45, black peak), demonstrating that the swab cleaning method did not extract significant amounts of pigment from the artwork.

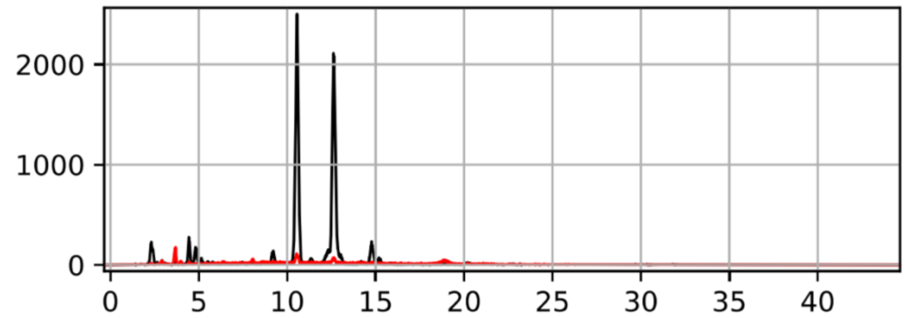


Figure 45. Comparative XRF analysis of lead (Pb) elemental peaks: the black peak represents the sky area of Landscape 1, while the red peak corresponds to the swab treated with DMSO blend. Foto: PyMca.

- *Landscape 2* fresh varnish
  No metal element shows in both reports of swab and tissue (Figs. 46 and 47).

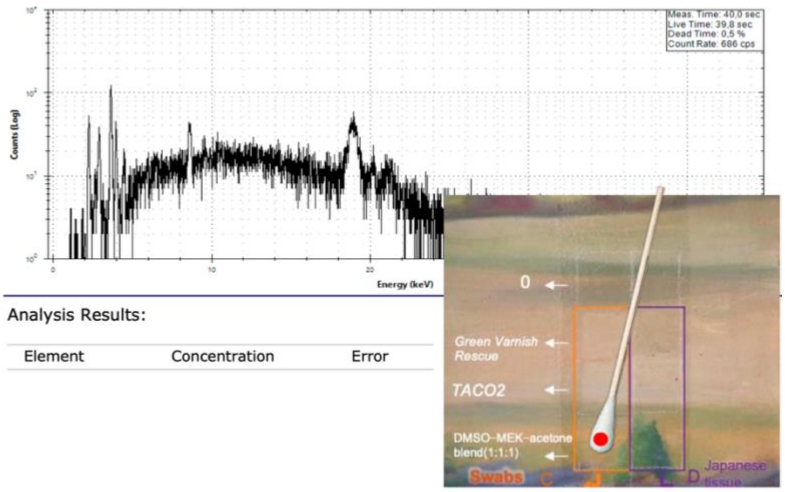


Figure 46. XRF report of swab (red dot) with DMSO blend after cleaning the fresh varnish. Foto:Bruker.

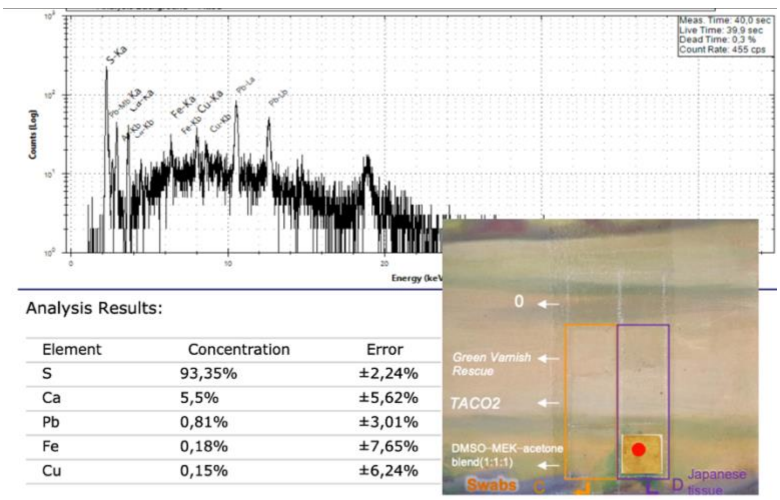


Figure 47. XRF report of tissue (red dot) with DMSO blend after cleaning the fresh varnish. Foto:Bruker.

Comparing the metal peaks from the swab cleaned with the DMSO blend to those from the grass area of *Landscape 2* shows no overlap between the two sets of peaks (Fig. 48). Therefore, the swab (and likewise the tissue) treated with this solvent did not pick up any original pigments.

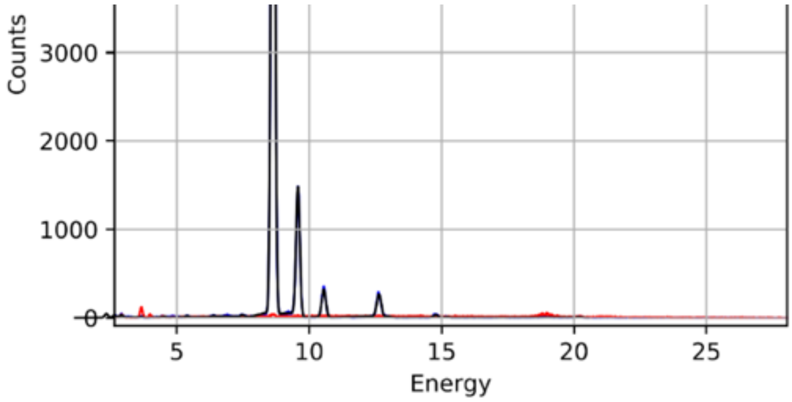
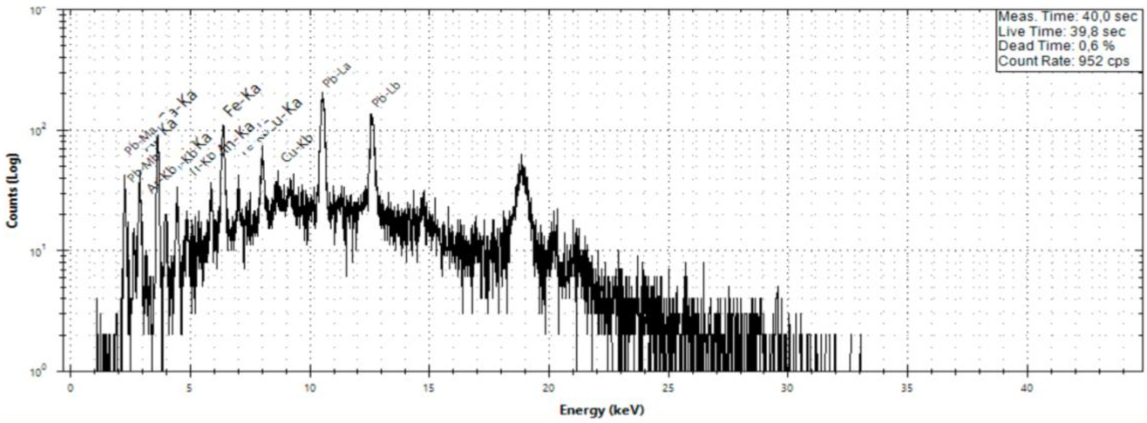


Figure 48. The metal peaks from the grass area of Landscape 2 (black) and those from the swab used with the DMSO blend after cleaning (red). Foto: PyMca.

In Solubility Test 1, the DMSO blend dissolved the brown pigment from the roof area of Landscape 1. Comparative analysis with clean cotton swabs revealed the presence of Fe and Pb elements in the post-cleaning swab samples (Fig. 49). Although the detected metal content (Pb and Fe) was minimal, the dissolved material exhibited a distinct brown coloration. Visual examination confirmed that this was not surface dirt but rather the dissolution of brown pigment.



Analysis Results:

Element	Concentration	Error
Ca	54,24%	±3,46%
Pb	23,9%	±1,95%
Fe	10,08%	±3,03%
Ti	6,53%	±6,86%
Cu	2,79%	±4,62%
Mn	2,47%	±6,87%

Figure 49. Fe and Pb elements were detected in the swab (red dot) after cleaning Landscape 1's aged varnish with DMSO blend. Foto: PyMca.

4 DISCUSSION

4.1 Solubility test 1

During the process of using the Fife Solvent Star to record and select solvents, both qualitative and quantitative observations were combined to assess cleaning performance. However, pigment loss is often difficult to detect visually—for example, the pale yellow in the sky area closely resembles the aged varnish. Although tests were performed in darker regions to improve visibility, the pigment composition in dark and light areas differs. Therefore, this method cannot be used to directly determine whether pigments across the entire painting are affected by the solvent.

As a result, the final solvent choice still relies on the conservator's experience, selecting the most suitable option from the five most promising candidates. The Fife Solvent Star also encourages conservators to reflect more on toxicity and environmental impact, which contributes positively to sustainability in the field.

In the DMSO blend, DMSO evaporates very slowly and relies on faster solvents like acetone to assist its evaporation. In *Landscape 2*, when a swab soaked with this blend was left stationary on the varnish for 60 seconds without mechanical action, blooming appeared (Fig. 50). However, no blooming occurred in the rolled area.

A possible explanation is that a high volume of solvent accumulated at a single point. Acetone, being highly volatile, evaporates rapidly and can cause surface cooling. If the temperature drops too much, moisture from the air may condense on the surface in the form of microdroplets, resulting in blooming. If water dissolves into the solvent mixture, it may cause the polymer to precipitate prematurely, resulting in blooming or a whitish blush. If the water is not miscible with the solution, it can remain on the surface, creating uneven or matte effects (Horie, 2011, p. 76).

However, no blooming was observed in the areas where the solvent was applied by rolling the swab, possibly because the amount of solvent on the surface was limited during movement. TACO2 contains up to 39% acetone and has a higher evaporation rate than the DMSO blend, yet no blooming occurred. It depends on how the solvent interacts with the varnish. If the solvent partially dissolves the varnish, blooming is more likely to happen on the "damaged" surface of the varnish. If the varnish is completely removed, the blooming is less likely to occur, and also if the varnish is not affected by the solvent.

After applying isooctane to the blooming area, the blooming disappeared (Fig. 51). Isooctane can dissolve a range of solvents, making it effective for removing residual cleaning agents. It is also capable of dissolving waxes and mild lipid residues and is considered a gentle solvent. Therefore, as a precautionary step, isooctane should be used at the end of all cleaning procedures to eliminate residual solvent and reduce the risk of long-term damage caused by solvent retention on the paint surface.

Figure 50. Blooming was observed after 30 minutes of treatment.

Figure 51. Blooming was removed after treatment with isooctane; blooming was no longer visible.

Based on the results from the Solvent Star Diagram for Recording Efficiency, GVR showed the highest overall performance on both aged and fresh varnish layers of the two historical oil paintings. It was the most effective removal, had the lowest toxicity, caused no pigment damage, and did not result in blooming.

4.2 Solubility test 2

In the swab and Japanese tissue comparison tests, the contact time was limited to 90 seconds. Longer exposure times were avoided due to findings by Baij et al. (2020, p.15), who reported that prolonged solvent contact with Evolon CR can promote the migration of fatty acids within the paint layer. These acids may react with metal ions such as zinc or lead, forming crystalline metal soaps.

Since Japanese tissue lacks the porous structure of Evolon CR, it absorbs less solvent and may allow more direct and extended contact between the solvent and the paint surface. This increases the risk of metal soap formation when free saturated fatty acids (SFAs) are present in the paint film (Baij et al. 2020, p.15).

Gels may be better for controlling solvent exposure and reducing penetration into the paint layer. However, potential gel residues must also be taken into consideration. There is no universally “best” solvent or method, only suitable combinations depending on the painting. An ideal solvent should not only remove aged varnish but also eliminate surface dirt or airborne pollutants.

Each painting requires a tailored approach, considering multiple factors. Initial solvent and carrier selection must be guided by the conservator’s experience and preliminary evaluation.

4.3 Evaporation Rate Test

In the Evaporation Rate Test, GVR had the slowest evaporation rate, TACO2 the fastest, and DMSO blend was moderate.

In another GVR’s experimental study, Macchia et al. (2021) reported that both MEK and GVR were effective in removing aged dammar varnish. However, MEK’s high volatility requires sufficient contact time, methods such as covering the surface with plastic film may be used to extend solvent action. On the other hand, Macchia et al. (2021, p. 2335) also emphasized that due to the low volatility of GVR, any residue must be removed manually with a dry swab after cleaning.

Solvents with smaller molecular volume and lower viscosity diffuse and swell oil paint more rapidly. For example, low-viscosity solvents such as acetone, benzene, and methanol produce faster swelling than larger, more viscous solvents like isobutanol (Phenix & Sutherland, 2001, p. 50). Polar solvents like acetone and ethanol can also cause leaching, where soluble components are extracted from the paint layer, increasing brittleness and density (Phenix & Sutherland, 2001, p. 54). Since both DMSO blend and TACO2 contain acetone, which has low viscosity and a small molecular size, they carry a greater risk of causing swelling and making the varnish layer more brittle compared to GVR.

Phenix and Sutherland (2001, p. 50) noted that natural resins become increasingly acidic as they age. Therefore, it is important to avoid direct contact with water and high-humidity environments during the cleaning process. In relation to the blooming (blanching) observed earlier, which may have been caused by moisture absorption from the air, it remains unclear whether blooming could also lead to a local increase in surface acidity. This question requires further research.

4.4 X-ray fluorescence (XRF) analysis

X-ray fluorescence analysis revealed no significant metal elements in the swab and tissue samples collected from light-colored areas, the sky in Landscape 1, and the grass in Landscape 2, following varnish removal. In Landscape 2, zinc (Zn) was detected in the grass area, while lead (Pb) was absent. This differential detection may be attributed to metal soap formation (Baij et al., 2020, pp.14 and 15). But metal soap complexes are hardly dissolved in many organic solvents which are used for cleaning varnish from paintings (Van Loon et al., 2021, p.229). However, the Zn peak intensity was minimal and visually insignificant. The presence of Zn in Landscape 2 suggests the potential use of zinc white, a pigment that gained widespread adoption only after the mid-19th century (Kühn, 1986, p.170). Conversely, the absence of Zn in Landscape 1 may indicate that the painting predates the common usage of zinc oxide pigments.

The DMSO blend was found to dissolve brown pigment from the rooftop area of Landscape 1. This phenomenon may be related to the "glaze" technique, which involves adding finishing touches by applying warm and dark pigment, oil, resin, or a combination of these between the varnish and paint layers. Such glazes are particularly susceptible to damage during cleaning treatments (Conti and Glanville 2007, p. 429). Mixing colors with resin to increase transparency is a common practice in Netherlandish Painting (Hermens & Townsend, 2021, p.212). These findings underscore the need for heightened caution when cleaning dark-colored areas, which may be more susceptible to solvent damage. The results further suggest that optimal cleaning may require different solvent approaches for light versus dark regions of the painting.

4.5 Solvents properties

Summary of the LD_{50}, boiling point, vapor pressure, flash point, and hazard labels for the nine individual solvents of the three solvent blends in Tab. 8. The data are sourced from each solvent's Material Safety Data Sheet.

Table 8. Properties of the Nine Individual Solvents

Solvent	Ingredients	Ratio	LD_{50} Oral (rat) mg/kg	Irritation	Boiling Point	Vapour Pressure kPa	Flash Point	Label elements
GVR	dioxolane	unknown	>2000	Eye-serious	75°C	9.3	-5°C	
	TOU	unknown	>5000	Eye-slight	202°C	0.022	84°C	
	DBE	unknown	>5000	none	195°C	0.1	100°C	
TACO2	isopropanol	15%	5045	Eye-serious	82°C	4.3	12°C	
	n-octane	46%	**5**	skin	124°C	1.86	13°C	
	acetone	39%	5800	Eye-serious	56°C	24	-17°C	
DMSO-MEK-acetone	DMSO	33.3%	28300	**Penetrates into the skin**	189°C	0.0556	87°C	
	MEK	33.3%	2483	Eye-serious	80°C	10.5	-7°C	
	acetone	33.3%	5800	Eye-serious	56°C	24	-17°C	

All data are from the solvent's Safety Data Sheets (Carl Roth, 2023). Below is a concise interpretation of the data in Table 8.

- The lethal dose 50 (LD_{50} Oral [rat]):
  A higher LD_{50} value corresponds to lower acute toxicity in rats (i.e., more of the substance is required to kill 50 % of the test animals) (Wexler & Hayes, 2019, p. 26).
- Boiling Point:
  The higher the boiling point, the less readily the solvent evaporates, which helps reduce both ambient air pollution and operator inhalation exposure.
- Vapour Pressure:
  A higher vapour pressure indicates greater volatility—i.e., the solvent evaporates more rapidly at a given temperature.
- Flash Point:
  The higher the flash point, the lower the fire hazard associated with the solvent (Horie, 2011, p. 78).

Solvents with flash points below 60 °C are typically classified as flammable liquids (Occupational Safety and Health Administration, n.d.).

4.6 Toxicity analysis

An important metric for assessing toxicity is LD_{50}, defined as the single-dose amount of a chemical that causes death in 50% of a group of experimental animals under specified conditions. LD_{50} values are inversely related to toxicity, i.e., the lower the LD_{50}, the more toxic the solvent (Wexler & Hayes, 2019, p. 26).

GVR is the least toxic of the three formulations, as all three of its components (dioxolane,TOU, and DBE) have oral LD_{50} values > 2000 mg/kg (Tab. 6). In contrast, TACO2 is the most toxic overall: one of its ingredients, n-octane, has an oral LD_{50} of just 5 mg/kg, and at a concentration of 46 %, n-octane makes TACO2 the most acutely toxic solvent in the group.

The DMSO blend exhibits moderate acute toxicity. All three components have oral LD_{50} values above 2000 mg/kg, with DMSO's LD_{50} of 28 300 mg/kg indicating particularly low toxicity. However, DMSO is a powerful skin penetration enhancer and when mixed with other hazardous substances, can carry them through the skin (Williams & Barry 2012). Williams & Barry also report that DMSO concentrations above 60 % induce erythema and wheal formation by altering keratin conformation in the stratum corneum. In the DMSO–MEK–acetone mixture, MEK and acetone evaporate rapidly while DMSO remains, so prolonged open-air exposure may raise the DMSO fraction above 60 %, increasing the risk of skin irritation. Moreover, DMSO permeates butyl rubber gloves at ASTM Level 6, and its Safety Data Sheet recommends glove replacement after eight hours' wear. Finally, inhalation of MEK vapors can depress the central nervous system and irritate eyes and skin. For these reasons, despite its relatively low intrinsic toxicity, the DMSO blend carries significant health risks.

In addition to its cleaning performance and safety profile, the chemical composition of GVR supports its classification as a sustainable solvent. Dioxolane, one of its key ingredients, can be sustainably produced from renewable biomass sources and has been studied for its use as an oxygenated hydrocarbon in fuel applications (Ahmad et al., 2019). Another component, dibasic ester (DBE), is recognized as an environmentally benign organic solvent and can be derived from plant-based byproduct streams, making it both biodegradable and low in toxicity (Hoerr & Harwood, 2002).

4.7 Flammability risk analysis

The packaging of GVR does not carry a flammable-liquid pictogram. One of its ingredients, dioxolane, has a very low flash point of –5 °C; dioxolane is classified as a flammable liquid. Its vapor pressure of 9.3 kPa is moderate to high relative to the other solvents tested. However, our evaporation-rate test showed that GVR evaporates more slowly than the other blends, implying that its dioxolane amount is kept to a minimum.
The remaining components, TOU and DBE, both have flash points above 60 °C and are therefore not considered flammable liquids. Consequently, GVR poses the lowest fire hazard of the three formulations examined.

4.8 Cost analysis

The prices for the three solvent blends are as follows: the cost of GVR is taken directly from the procurement invoice for the entire bottle. In comparison, the prices for the other two blends were calculated based on the suppliers' list prices (Merck KGaA, 2025 and Att.1) for their components (Tab. 9).

Table 9. Solvent costs and calculated prices per 100 g based on component proportions.

Solvent	Ingredients	ratio	Price Euro/kg	Euro/100g	Manufacturer
GVR	GVR	1	20	**2**	YOCOCU
TACO2	Isopropanol	15%	37	(0.15×37 + 0.46×323 + 0.39×90) ×0.1 = **19**	SeccoSolv®
	n-Octane	46%	323		Sigma-Aldrich
	acetone	39%	90		Supelco
DMSO-MEK-acetone	DMSO	33.30%	163	(163 + 107 + 90) /3×0.1 = **12**	Kremer pigmente
	MEK	33.30%	107		Supelco
	acetone	33.30%	90		Supelco

The cost per 100 mL is €2 for GVR, €19 for TACO2, and €12 for the DMSO blend. Thus, GVR is far more economical to use than either TACO2 or the DMSO blend.

4.9 Limitations of the Study

First, this study is based on only two paintings, which limits the generalizability of the results. A larger sample size that includes a broader variety of varnish types and painting conditions would provide a more comprehensive assessment of GVR's performance and solubility.

Second, the aged varnish on *Landscape 1* was of unknown composition. Varnishes made from different resins, such as dammar, mastic, or synthetic formulations, age at varying rates and exhibits distinct solubility profiles. Without chemical characterization of the varnish, the observed results may not fully reflect the solvent's effectiveness across all varnish types. Future studies should include varnishes with well-documented compositions to enable a more accurate evaluation of GVR's advantages and limitations.

5 SUMMARY AND CONCLUSIONS

This study systematically evaluated the effectiveness of GVR as a green solvent alternative for varnish removal, compared to two traditional solvent mixtures: TACO2 and DMSO blend. The research addressed two key questions:

- Effectiveness of GVR in removing aged and fresh varnish

  The results demonstrated that GVR was highly effective on both aged and freshly applied varnish layers. On aged varnish (*Landscape 1*), it achieved complete removal with controlled swelling and less pigment loss, outperforming TACO2 (which evaporated too quickly) and the DMSO blend (which risked pigment dissolution). For fresh varnish *(Landscape 2*), GVR provided the cleanest results with minimal residue, while traditional solvents left uneven residues or caused blanching. Its slower evaporation rate allowed for better controllability during application.

- Potential to replace traditional solvent mixtures

  The study confirms that GVR can serve as a viable replacement for traditional solvents in aged varnish cleaning, particularly where safety and environmental impact are prioritized. Its non-toxic, biodegradable, and low-volatility properties reduce health risks for conservators and minimize the need for specialized ventilation. However, its slower evaporation may require additional steps (e.g., manual residue removal), and XRF analysis suggests that it may also remove trace amount of pigment elements under certain conditions. This finding highlights a potential risk to the underlying paint layer, indicating the need for further investigation before widespread usage.

Solvent testing should begin in areas beneath the frame, as the paint layer there is usually better preserved. One should start with solvents of lower polarity and gradually test stronger, more polar solvents. Tests should first be conducted on light-colored areas, since darker colors may be more sensitive. The Fife Solvent Star is good to use to record the efficiency and effectiveness of dissolution. Controlled solvent application methods, such as gel cleaning, are recommended to avoid prolonged local wetting and reduce the risk of metal soap formation.

The findings fit well with conservation principles of minimal intervention and sustainability. GVR's performance supports its adoption in cases where aged varnish removal demands precision without compromising underlying layers. However, conservators must still tailor solvent choices to specific varnish types and painting conditions.

As a result, conservators must continue to tailor solvent selection carefully, taking into account the specific varnish composition, pigment characteristics, and the overall condition of the artwork.

To advance the practical application of sustainable solvents in conservation practice and achieve sustainable development in the field of restoration, future research should prioritize the following directions for in-depth investigation:

- Investigate long-term effects on paint film integrity after cleaning.
- Explore the combination of sustainable solvents with gel systems, emulsions, or nanomaterials to improve controlled application and reduce solvent penetration into vulnerable paint layers.
- Study the causes of blooming in greater depth, particularly the role of humidity and solvent composition, to develop preventive strategies.
- Conducting lifecycle analyses to quantify the carbon footprint and cost-effectiveness of sustainable solvents compared to conventional alternatives in real-world conservation workflows.

In conclusion, GVR emerges as the least toxic and most environmentally benign of the three solvents tested. It carries the lowest health risk, imposes minimal environmental impact, and entails the most economical storage and production costs. While practical adoption may require some adjustments to current conservation workflows, it nevertheless offers a safer, more efficient, and cost-effective alternative for varnish removal.

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7 LIST OF FIGURES AND TABLES

Figures

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8 Attachments

Attachment 1. GVR purchase receipt.

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Riferimento:

Numero Preventivo 294 del 07/04/25 Pag. 1

Pagamento BONIFICO ANTICIPATO
IBAN Banca di appog
IT64 Z083 2703 2010 0000 0038 020

Articolo	Descrizione	UM	Quantità	Prezzo	Sconto	Importo scontato
1521/A	Green Varnish Rescue Kg. 1	KG	2	20,0000		EURO 40,00