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Development of a Natural Surface Coating for Clay-Based Surfaces based on Historical Practices

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ABSTRACT

Clay has been one of the earliest and most versatile building materials, essential for bricks and as a binder for plaster on earthen walls. Despite advancements in surface coatings, there is limited research on coatings specifically for clay-based surfaces. This study addresses this gap by developing a novel clay coating inspired by ancient Sri Lankan techniques. Key ingredients include Pine gum, Haldummala (Shorea oblongifolia), Dorana (Dipterocarpus glandulosus) oil, and ethanol. Fifteen samples with varying Haldummala concentrations (2-10 g in 2 g increments) were tested. Sample 2, with 4 g/L of Haldummala, showed superior properties: a density of 0.9529 kg/L, 55.48 % solid content, 21 seconds viscosity, 10.48 % opacity, and 33.5 gloss units at 60 °. No peeling, cracking, or blistering occurred after 500 hours of artificial aging in QUV tests. Both natural and commercial coatings showed similar gloss reductions (9-12 %) but retained over 80 % of their initial gloss, demonstrating strong UV resistance. The natural coating also achieved a permissible VOC content of 3.5 lb/gal. The carbon footprint analysis revealed that the natural coating emitted 1210 kg CO_2-equivalent, 61.9 % lower than the 3180 kg CO_2-equivalent of its commercial counterpart. This significant reduction highlights its environmental sustainability. Overall, the new formulation proved to be a durable, eco-friendly, and effective coating for clay-based surfaces, offering a viable alternative to conventional options. Prog. Color Colorants Coat. 18 (2025), 295-312© Institute for Color Science and Technology.

1. Introduction

Clay is one of the oldest building materials, commonly used in hot and temperate regions. Since 7000 B.C., it has been used as mortar, plaster, or a main ingredient in bricks and earthen walls [1]. In recent decades, clay has received significant attention as a key component in mortars and plasters, becoming a popular material in modern construction practices. It is also a binder in composite materials made from straw or shives [1]. Clay is gaining awareness because of its absorbing and vapor permeability properties while aligning with the rising demand for sustainable, eco-friendly buildings. This trend has increased interest in earth mortars made from natural materials like clay and lime, which have a low carbon footprint [2]. Clay is increasingly recognized as an environmentally friendly building material due to its

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natural properties and potential for innovative applications. This ancient material is being modernized with advanced composites and biopolymers, enhancing its performance and making it suitable for energy-efficient and resilient designs [3]. Non-fired clay materials, reinforced with biopolymers such as starch and alginate, exhibit enhanced mechanical properties, making them more suitable for building materials [4]. The specific heat and thermal conductivity of clay optimize rammed earth wall performance by regulating indoor humidity and reducing energy consumption [5]. The heat flow dynamics in rammed earth walls perform better than traditional materials [5]. Despite its positive attributes, clay is hindered by challenges related to its structural stability and the regulatory processes it must undergo [3]. Advancements in clay composites and the incorporation of natural additives such as starch show great potential for improving the mechanical properties of clay [6]. Although clay possesses numerous advantages, its inherent variability and susceptibility to instability in certain conditions demand meticulous consideration in construction applications [7].

Coatings for clay building materials enhance their durability, energy efficiency, and moisture resistance. Various coatings, including engobe, polymeric, and hydrophobic, have been developed to address the challenges posed by the porous nature of clay materials. These coatings not only protect against moisture ingress but also improve the mechanical properties and longevity of the materials. Various protective coatings have been developed to enhance the durability and sustainability of clay building materials, each offering unique benefits. Engobe coatings seal the porous structure of ceramic bricks, reducing water absorption from 14.8 % to 3.2 % and increasing frost resistance from 15 to 65 cycles [8]. They significantly extend the service life of bricks by preventing moisture-related damage. Polymeric coatings enhance abrasion resistance and can be applied using various methods such as electrostatic and HVLP [9]. These coatings are beneficial for their reusability and low VOC emissions, making them environmentally friendly. Hydrophobic coatings improve water resistance, reducing water absorption by over 50 % and enhancing the protection degree to 100 % [10]. They maintain the breathability of masonry while providing robust moisture regulation. In contrast, while these coatings offer significant benefits, they may also introduce challenges such as increased costs and potential application failures, necessitating careful selection and application methods to optimize performance [9].

Hybrid coatings that combine organic and inorganic materials improve hydrophobic properties and reduce water absorption by over 50 %, achieving a protection degree of 80-100 % [10]. Additionally, super-hydrophobic multifunctional coatings (SMC) can decrease capillary water absorption by 92.91 % and provide self-cleaning and thermal insulation properties [11]. In adobe constructions, compatible plaster coatings enhance water resistance and adhesion, which is crucial for durability [12]. Lastly, low-carbon additives improve the mechanical properties of clay, offering a sustainable alternative to traditional materials [13]. These advancements highlight the importance of selecting appropriate coatings for enhancing clay material performance.

Coatings like paints and whitewashes exhibit significant degradation over time, reducing the effectiveness of clay-based materials [14]. Super-hydrophobic coatings, while beneficial, struggle with long-term durability and bonding to clay materials [15]. Coatings must withstand environmental factors such as moisture and freeze-thaw cycles, which can compromise their integrity [15]. Organic-inorganic coatings can help, but their performance depends on the specific formulation [16]. Intumescent fire-retardant coatings (IFRC) are also commonly applied for fire protection in timber and construction structures [17]. Additionally, fire-retardant-treated wood (FRTW) coatings with outstanding optical properties have also been explored in the studies [18].

Despite advancements in coating technologies, the persistent issues of durability, adhesion, and environmental resistance highlight the need for ongoing research and development. New materials and methods may be required to overcome these challenges effectively. Further research is essential for further understanding the interaction between surface coatings and clay-based walls. In particular, there have been cases where inappropriate modern paints, when applied over traditional clay or lime finishes, have resulted in moisture entrapment and subsequent degradation of the underlying materials [19, 20]. These failures emphasize the compatibility between coatings and substrate materials and the need for practitioners to be mindful of the traditional building methods that characterize earthen construction.

When examining ancient coating technology in Sri

Lanka, Buddhist wall painting techniques, which originated in the 2nd century BCE, evolved systematically with increasing visual intricacy from the 2nd century CE, continuing to develop and endure to the present day. These paintings were created on clay or soil-based surfaces. The artworks from the early Anuradhapura period (247 BCE to 800 CE) and the Polonnaruwa period (12th to 13th CE) are distinguished styles characterized by the use of plant glue, drying oil, or plant extracts mixed with lime or clay mortar. This mixture, known as the tempera technique, was employed for painting purposes on clay-based surfaces [21].

Oil paints have remained a widely used medium due to their versatility, range of effects, and extended open time, which allows for sophisticated blending and reworking. At their core, oil paints are composed of pigments ground into a drying oil. These oils dry by oxidation to form a coherent film, in contrast to resins and gums, which dry by the evaporation of the diluent. Transparent coatings have likely always been considered protective layers for oil and tempera paintings on clay-based surfaces [22].

Given the historical context, it is evident that the protective layer of paintings done on clay-based surfaces in Sri Lanka is composed of a blend of plant gum, Dorana oil, and Haldummala [23]. "Haldummala" (or "Dummala") refers to a naturally occurring substance found in the uppermost layers of the earth's crust, often beneath freshwater marshy areas, or as a dried resin similar to gums. Dorana oil, derived from the Dorana tree (*Dipterocarpus glandulosus*), has been combined with other organic substances to paint murals in ancient Sri Lankan temples [24]. Dorana oil serves as a binder for paint and a preservative coating known as valitti. According to Seneviratne [19], when clean Dummala powder is mixed with Dorana oil and boiled, it dries and imparts a deep shine when applied to a surface.

This study combined Dorana oil and Haldummala with Pine gum resin and ethanol to develop a novel coating for clay-based materials. The proportion of Haldummala was varied to assess its effects on the coating's performance. Characterizing the developed coating involved evaluating its properties, including density, solid content percentage by mass, viscosity, opacity, and gloss, per ASTM and ISO standards. Subsequently, the novel coating was evaluated for its properties compared to commercially available coatings. The study included a detailed analysis of VOC emissions and artificial aging performance. Additionally, sustainability criteria were assessed through a carbon footprint analysis. Overall, this study aims to develop a varnish inspired by traditional practices, focusing on protecting and enhancing clay-based surfaces.

2. Experimental

This study examined the potential of a coating formulation comprised of Dorana oil, Ethanol, Pine gum, and Haldummala, drawing inspiration from historical practices. The developed coating was subsequently applied to a contemporary soil-based surface, mud wall care putty (Patent no. 21020) [25]. The materials used and the methods employed are described in detail in Sections 2.1 and 2.2.

2.1. Materials

The studies [21, 23, 26], conducted detailed instrumental analyses of plaster, pigments, and preservative coatings used in Sri Lankan mural paintings on clay-based surfaces. These investigations included the techniques, conservation history, and scientific examination of paintings from notable sites such as Sigiriya, Tiwanka Image House, Dambulla Cave Temple, and Mirissa Samudragiri Viharaya in Sri Lanka. Key findings included the identification of binding mediums, protective coatings, and painting techniques employed by ancient artists. Based on these insights, studies [26, 27] initiated the prototyping of coatings, incorporating historical formulations. The present study selected materials inspired by these historical formulations and further enhanced them with modern solvents and resins, building on this foundation. Ethanol was introduced as a suitable solvent, pine gum and Haldummala were used as resins, and Dorana oil was incorporated as the drying oil, with the concentration of the traditional resin Haldummala varied to evaluate its performance more effectively. To comprehensively evaluate its effect on coating performance, the Haldummala resin concentration was varied systematically between 2-10 g/L. This range was chosen based on its compatibility with ethanol and documented historical usage [23].

2.1.1. Resins

The new coating formulation used two natural resins: Pine gum and Haldummala. Haldummala, also known as Dummala, is a substance found in the upper layers of the earth's crust, often near freshwater marshes. It can also refer to a dried resin similar to that from the

Dummala tree (*Shorea oblongifolia*), native to Sri Lanka. With a history spanning over 2000 years, Dummala has been used in Ayurvedic medicine and traditional rituals. When extracted, it appears as a peat-like, coarse-grained material [24].

Research on Sri Lankan wall coating techniques reveals that ancient Sri Lankans used a combination of Drying oil and Dummala for their coating applications [28-30]. This practice is notably mentioned concerning the wall paintings at Sigiriya, Thiwnake, and Rangiri-Dambulla, where scholars have highlighted the use of Dummala alongside Dorana oil for the protective coating of these paintings [23]. Furthermore, the traditional Sri Lankan varnish, known as "Vaiti," was created by mixing boiled Dummala with Dorana oil for use in painting [28].

Pine gum, specifically rosin resin, is commonly used in varnish production due to its composition of rosin acids, particularly abietic acid. These acids facilitate polyurethane formation, a protective coating that safeguards the surface from chemical and environmental damage [31]. Pine gum comprises a complex blend of organic compounds, which include terpenes, resin acids, phenolic compounds, and other hydrocarbons. These components contribute to its stickiness and ability to fend off pests and microbial infections. The exact makeup can vary based on the pine species and environmental conditions [32]. Terpenes like α-pinene and β-pinene are key ingredients in pine gum, giving it its distinctive smell and contributing to its antimicrobial properties. Resin acids, such as abietic acid and pimaric acid, give the gum adhesive and protective functions [28].

2.1.2. Binders

Dorana oil, extracted from the Dorana tree, is a traditional Sri Lankan product. When mixed with other natural materials, this oil has been used in ancient Sri Lankan temples to create beautiful murals [33] It has also served as a paint-binding agent and a protective coating called *valitti*. Additionally, when combined with Dummala powder, it forms a quick-drying mixture that produces a glossy finish on surfaces [21]. According to the FTIR spectroscopy analysis conducted in Seneviratne's study [19], Dorana oil exhibits a higher concentration of C=C double bonds than other drying oils, leading to a more rapid curing process. Additionally, Seneviratne's findings identified the presence of several compounds in Dorana oil, including Sitosterol, Dipterocarpol, β-amyrin ($C_{30}H_{50}O$), Copalliferol A, and Copalliferol B [19]. These components collectively enhance the binding properties of Dorana oil.

2.1.3. Solvents

Ethanol is an effective varnish solvent, offering numerous benefits in formulation and application. It is especially valuable in environmentally friendly varnishes, replacing more hazardous solvents, improving user safety, and reducing environmental impact [34]. Ethanol is an essential ingredient in various varnish mixtures, including those with polyamide and nitrocotton, which are soluble in alcohol and help minimize toxic emissions. It also plays a key role in high-solids solutions of rosin esters, demonstrating excellent solubility and suitability for humans and animals, underscoring its versatility. Ethanol is also a critical component in eco-friendly varnishes, helping lower the environmental footprint while maintaining high performance [35]. Varnishes that incorporate ethanol offer desirable qualities, such as low production costs, excellent color retention, and minimal yellowing, making them particularly well-suited for digital printing applications [34].

2.2. Methods

In this study, the drying oil and solvent were mixed in a ratio 80:20 (by volume) for the coating formulation. Given the solubility of pine gum, a pine gum concentration of 4 g/L was maintained in the ethanol. The concentration of Haldummala was varied between 2 to 10 g, with increments of 2 g, to assess its impact on the coating system's performance. A total of 15 samples were used for this study. The samples were conditioned for 7 days in a room with a temperature of 20±2 ºC and relative humidity of 50% ± 5% before any tests were carried out. Key properties, including solid content percentage by mass, density, opacity, viscosity, and gloss, were evaluated following the methods outlined in Sections 2.2.1 to 2.2.5. Each test was conducted in triplicate, and the average of the three measurements was used for subsequent data analysis.

2.2.1. Density

For higher precision when working with non-pigmented materials (drying oils, varnishes, resins, and related materials), the ATSM D1963 test method was used.

Density is defined as the mass per unit volume and is a fundamental property for identifying, characterizing, and ensuring the quality of various materials. The Elcometer 1800 Density Cup (Pycnometer) was employed to measure density in this study. The necessary weight measurements were obtained using a laboratory scale.

2.2.2. Solid content percentage by mass

The test method ASTMD2369-24 was used. The procedure determines volatiles in coatings and calculates the volatile organic content in coatings under specified test conditions. The weight percent of solid content (non-volatile material) is derived by subtracting the volatile components. Small cups were made from aluminum foil, with three cups for each sample. The weight of the cups, both with and without the sample, was measured. The cups were then oven-dried for 3 hours, and the residue solid content was calculated.

2.2.3. Viscosity

The test method ASTM D1200 was used. It covers the determination of the viscosity of Newtonian or near-Newtonian paints, varnishes, lacquers, and related liquid materials with the Ford-type efflux viscosity cup. The method employs a Ford-type efflux viscosity cup, a calibrated device with an orifice at the bottom designed to measure the time required for a specific volume of liquid to flow through the orifice under gravity. This flow time is then correlated to viscosity. The test is particularly suited for materials with relatively low viscosities and is widely used in quality control to ensure the consistency and performance of liquid coatings during application.

2.2.4. Opacity

The test method D2805 was used. It describes an instrumental method for determining hiding power. The paint film is applied uniformly, the film thickness is measured rigorously, and the opacity is determined photometrically. This instrumental technique evaluates hiding power by applying a paint film of uniform thickness, rigorously measuring the film's thickness, and then assessing the opacity using photometric analysis. To perform a drawdown card test, paint is applied to a Leneta Chart, a specialized paper with alternating black and white strips. The paint is evenly spread using a drawdown bar to create a thick film over the chart. Once the paint has dried, the reflectance of the film is measured on both the black and white areas.

2.2.5. Gloss

The ASTM D523 test method was used. It explains the measurement of gloss on non-metallic samples. The specular gloss measurement is performed for the light reflected from the material surface. GLOSS 503 gloss meter (ERICHSEN GmbH, Hemer, Germany) was used. The gloss measurements were conducted at a degree level of 20°and 60° geometry, parallel and perpendicular to the sample. Five measurements per sample were taken for each standardized measuring angle and direction according to the ISO standard.

3. Results and Discussion

The data from the tests in Section 3.0 were analyzed using Python. The performance parameters were both normalized and standardized to ensure fair comparisons. Standardization is particularly useful when property values have different ranges, bringing them to a common scale. Figure 1 shows the Normalized properties across different samples. A heatmap (Figure 2) was then used to visually represent the scores for all coatings and criteria, making it easier to identify high-performing coatings at a glance.

As shown in Figure 1 and Figure 2, Samples 2, 3, 4, and 5 exhibit similar performance patterns across most properties, with consistently high values observed in key parameters.

In contrast, Sample 1 presents several notable deviations, including:

- Lower density values
- Higher viscosity, which may suggest potential challenges in application
- Reduced solid content

Among the samples, Sample 2 stands out as the best-performing coating, demonstrating:

- Optimal solid content
- Excellent gloss properties
- Well-balanced viscosity
- Stable density
- Good opacity
- Slightly lower gloss values compared to other high-performing samples, but still within acceptable limits.

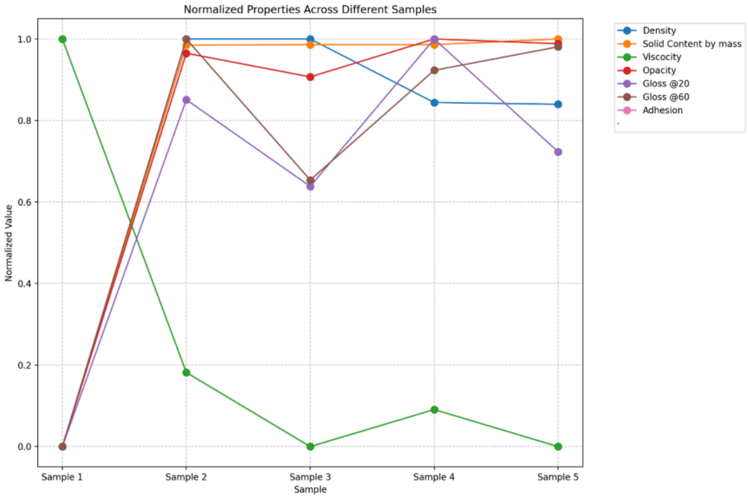

Figure 1: Normalized properties across different samples.

Figure 2: Property Performance Heat Map.

In this study, while Samples 2, 3, 4, and 5 exhibit similar high performance across most properties, Sample 2 stands out as the top-performing coating due to its optimal balance of key parameters, including solid content, gloss, viscosity, density, and opacity. Despite Sample 1 showing some significant deviations in density, viscosity, and solid content, Sample 2's superior combination of characteristics makes it the most reliable choice for performance, highlighting its potential for practical applications. These findings underscore the importance of balancing multiple properties in selecting the most effective coating for specific performance criteria.

The fundamental characteristics of coatings and paints; density, viscosity, gloss, opacity, and solid content - play pivotal roles in determining their performance efficacy and application methodology. Research has demonstrated that density significantly impacts coating coverage and durability [36] while viscosity governs flow characteristics and application uniformity [36, 37]. Studies by [38, 39] have established that gloss levels contribute to aesthetic appeal and practical attributes such as cleanability and durability. Opacity, often called hiding power, is crucial for application efficiency, with higher opacity levels reducing the necessity for multiple coats [39, 40]. Recent investigations by [41, 42] have highlighted the significance of solid content in determining film thickness, durability, and environmental impact through VOC reduction. However, these properties exhibit complex interrelationships, necessitating careful formulation to achieve optimal balance. For instance, while increased solid content may enhance durability, it can adversely affect viscosity and application characteristics, highlighting the importance of precise formulation strategies for specific applications [36].

3.1. Comparative evaluation of novel coating formulations versus commercially available varnish

In this study, a comprehensive comparative analysis was conducted to evaluate the performance properties of the novel coatings, including density (kg/L), solid content (% by mass), viscosity (BS B4, seconds), gloss at 20° and 60° on soil-based panels, gloss at 60° on drawdown cards, opacity on drawdown cards, drying time, wet film thickness (WFT) on wood panels (µm), pencil hardness (scratch resistance), and cross-hatch adhesion (damage percentage). Artificial aging tests were performed using QUV test cycles to assess durability, while volatile organic compound (VOC) levels were measured and compared against permissible standards. Furthermore, the carbon footprint of the novel coating was calculated and benchmarked against commercially available solvent-based paints to evaluate its environmental impact.

3.1.1. Sample preparation and application

In this study, coating was applied on the recently innovated mud wall care putty (Patent no. 21020) [22]. It is a soil-based wall care putty developed from drinking water treatment plant waste alum sludge comprising dry alum sludge powder mixed with 10% cement or lime. The soil-based wall care putty was prepared and applied to 2×4-inch concrete samples (Figure 3). The putty was then sanded using 320-grit sandpaper to achieve the desired surface roughness. After allowing the samples to dry for 7 days (Figure 4), a coating was applied using a brush in a two-coat application process. A light sanding with 2000 grit sandpaper was performed between the two coats to ensure smoothness and adhesion.

3.1.2. Comparative analysis

This study conducted a comparative analysis through commercial laboratory testing to evaluate the performance of a newly developed varnish relative to a reference standard, Nippon Super Gloss Varnish. The analysis focused on key physical and performance properties, comparing five formulations of the new varnish against various parameters, including density, solid content, viscosity, gloss at multiple angles, opacity, drying time, wet film thickness (WFT), pencil hardness, and cross-hatch adhesion (damage percentage) as shown in Table 1. These tests were designed to assess the durability, surface finish quality, and practical application characteristics of the new varnish formulation compared to a commercial high-gloss varnish. Key findings include notable observations regarding gloss retention at varying angles, hardness, and drying efficiency. These factors are critical for evaluating the suitability of the new varnish for high-performance coating applications and surface protection.

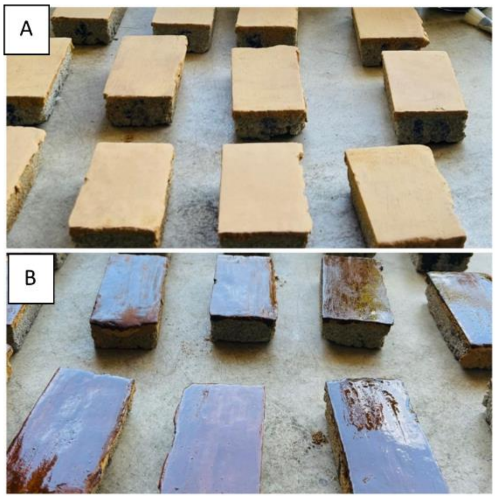

Figure 3: A) Samples before application B) Samples immediately after application.

Figure 4: Samples after being allowed to dry for 7 days.

Table 1: Property test result comparison.

Test properties	S.G. VARNISH	SAMPLE 1 (2 g/L)	SAMPLE 2 (4 g/L)	SAMPLE 3 (6 g/L)	SAMPLE 4 (8 g/L)	SAMPLE 5 (10 g/L)
Density (kg/L)	0.9029	0.9298	0.9529	0.9529	0.9493	0.9492
Solid content % by mass	59.85	48.41	55.48	55.49	55.49	55.59
Viscosity bs b4 (s)	183	30	21	19	20	19
Gloss @ 20° on soil-based panel (GU)	Not applicable	22.7	6.3	6.2	6.7	9.4
Gloss @ 60° on soil-based panel (GU)	87	58.1	33.5	31.9	44.8	40.4
Gloss @ 60° on drawdown card (GU)	95	74.5	93.7	94.6	86.7	84.2
Opacity on drawdown card (%)	9	9.65	10.48	10.43	10.51	10.50
Drying time (Hrs)	¾- 1	3-4	3-4	3-4	3-4	3-4
WFT on panel (μm)	120 - 127	127	127	Below 127	Below 127	Below 127
Pencil hardness test (scratch resistance)	4B	4B	4B	3B	3B	3B
Cross-hatch damages (%)	0	0	0	0	0	0

The data shown in the Table 1 was analyzed using Python. The performance parameters were both normalized and standardized to ensure fair comparisons. And a composite score was developed. The composite score for each sample is calculated by considering the percentage deviations from the commercial varnish, weighted by the importance of each property. The scores were normalized to a 0-100 scale, where a higher score indicates a closer match to the commercial varnish. The composite score comparison is shown in Figure 5. The analysis identified Sample 2 as the best-performing sample with the highest composite score.

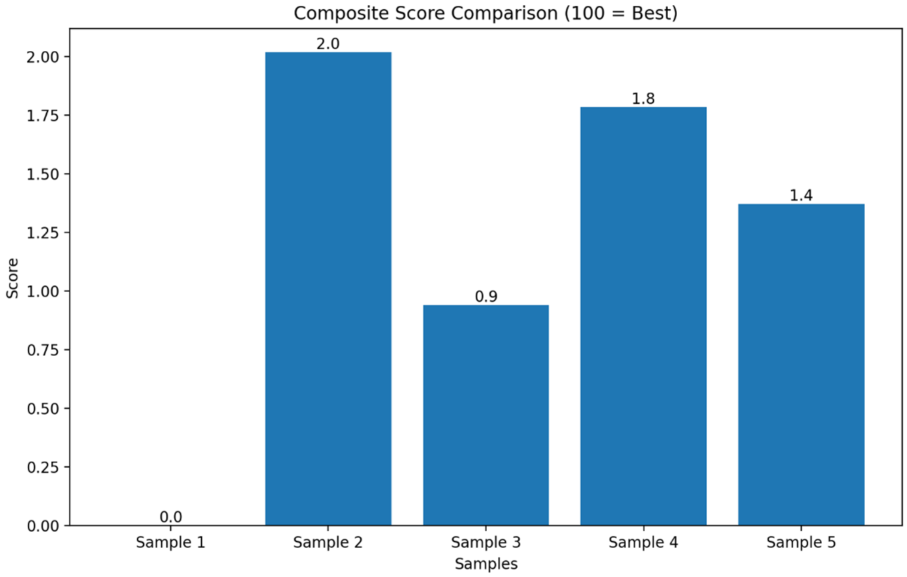

Figure 5: Composite score comparison.

Final Normalized Scores as shown in the Figure 4:

- Sample1: 0.00
- Sample2: 2.02
- Sample3: 0.94
- Sample4: 1.78
- Sample5: 1.37

The best-performing sample was Sample 2, with a score of 2.02. The density of Sample 2 deviated by 5.54 % from that of the commercial varnish. Density plays an important role in the formulation of coatings, as it influences the overall weight and spreadability of the product. While the deviation is relatively moderate, it could affect the final coating's application and performance, particularly regarding coverage and film formation. Sample 2 exhibited a 7.30 % deviation in solid content compared to the commercial varnish. Solid content is a critical parameter that determines the amount of material on the substrate after the solvent evaporates. A higher solid content typically leads to a thicker, more durable film, while a lower solid content may reduce the final coating's overall robustness and durability. The deviation observed in Sample 2 may indicate potential differences in application properties and performance relative to the reference varnish. The viscosity of Sample 2 showed an 88.52 % deviation from the commercial varnish, which is a significant difference. Viscosity, which measures a fluid's resistance to flow, is a key property in coating formulations, affecting both the application and final coating performance. The commercial varnish's higher viscosity suggests it is more resistant to flow than the novel varnish. Higher viscosity coatings tend to be thicker, which may result in more difficult application control, especially during spray applications. Thinning the paint to the correct viscosity allows for a wider and more even spray pattern, ensuring better coverage [36, 38]

ISO standards for wall coatings establish benchmarks for various properties to evaluate their performance and suitability for specific applications [43]. Gloss is a key indicator of finish type, with matte finishes typically exhibiting values between 0 and 10, eggshell between 10 and 30, satin between 30 and 50, semi-gloss between 50 and 70, and high gloss exceeding 70 [43]. The novel coating developed in this study exhibited a gloss range of 30-50, categorizing it as a satin finish. Density for wall coatings typically ranges from 1.2 to 1.5 g/cm³ for water-based coatings and 1.3 to 1.7 g/cm³ for solvent-based coatings [43]. However, both the commercial and natural surface coatings in this study exhibited a significantly lower density of around 0.9 g/cm³, suggesting the presence of lighter or more porous components, potentially due to natural ingredients. Viscosity, measured in seconds using a Ford cup, typically ranges from 20 to 40 seconds for matte finishes, 15 to 30 seconds for gloss finishes, and up to 50 seconds for heavy-duty coatings [43]. The coating developed in this study had a viscosity range of 19-30 seconds, placing it within the range for gloss varnishes, indicating a moderate flow and application behavior suitable for smooth, clear coatings. Opacity, which indicates the ability of the coating to cover underlying surfaces, typically ranges from 95 to 99 % for standard wall paints [43]. However, since the coating developed in this study acts as a varnish or clear coating for soil-based walls, the opacity was around 9 %, a characteristic typical of clear coatings. As such, opacity benchmarks for traditional paints do not apply to this varnish type. The solid content in water-based paints is typically between 30 and 50 %, while solvent-based paints have solid content ranging from 50 to 70 % [43]. The coating developed in this study had a solid content of approximately 55 %, aligning with the solvent-based paints benchmark. These values provide general guidelines for the properties of wall coatings, but for soil-based surfaces, it is important to note that specific standards, such as those from ISO, are not readily available, and the unique composition of these coatings must be considered when determining their performance and suitability for use.

3.1.3. Artificial aging of novel coating

The QUV accelerated aging testing machine (GW-338) was utilized for artificial aging. The QUV tester replicates outdoor weathering conditions such as sun exposure, rain, dew, and temperature variations. It employs UV fluorescent lamps, a condensation mechanism, a water spray system, and temperature regulation to simulate realistic environmental conditions, allowing for the assessment of a product's durability in outdoor settings. A test cycle of 500 hours was used.

Test Cycle

- The QUV test cycle alternated between UV exposure and condensation
  - 8 hours of UV light at a set temperature (60 °C).
  - 4 hours of condensation at a lower temperature (50 °C).

Table 2: Test results of artificial aging after 500 hrs.

	Natural Surface Coating			Commercially Available Super Gloss Varnish		
Test properties	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Initial gloss @ 60 °	58.1	44.8	39	87	75	80
Gloss after 500 Hrs	52.6	39	35	79	66	71
Color difference-De	0.7	0.65	0.7	0.8	0.7	0.7
Observations	No peeling, cracking or blistering					

Six samples were analyzed in this study, including three derived from the natural surface coating and three additional samples from commercially available super gloss varnish for comparative analysis. The test results are presented in Table 2.

When considering Table 2, the gloss reduction is likely due to surface erosion, microcracking, or chemical degradation of the coating materials under UV radiation and other environmental factors simulated during the test. UV light can break down organic compounds in the coatings, leading to surface roughening and loss of reflectivity [44]. The QUV test results revealed that both natural and commercial surface coatings exhibited similar gloss reductions, ranging from 9 to 12 %, with the natural coatings showing reductions of 9.46, 12.9, and 10.02 %, and the commercial coatings showing reductions of 9.19, 12, and 11.25 %. This indicates that both coatings retained over 80 % of their initial gloss after 500 hours of exposure, demonstrating good resistance to UV-induced degradation. The comparable performance suggests that natural coatings, despite potentially lacking advanced UV stabilizers found in commercial coatings, can still provide durability and effective protection against photochemical breakdown. This underscores the potential of natural coatings as viable alternatives to commercial options, particularly in environmentally sustainable applications, while highlighting the possibility for further optimization to enhance their longevity and durability.

3.1.4. VOC calculation of novel coating

Architectural decorations are a significant source of anthropogenic volatile organic compound (VOC) emissions and contribute notably to indoor air pollution. This, in turn, can adversely affect occupants' comfort, health, and productivity [45]. The Environmental Protection Agency has established regulations to control volatile organic compounds (VOCs) in building and decorative materials. These regulations promote eco-friendly construction materials, enforce strict limits on harmful substances in building products, and aim to eliminate coatings and adhesives that contain solvents. Given these requirements, it's essential to accurately measure and understand VOC emissions from building and decorative materials to help prevent the formation of secondary pollutants and protect people from exposure risks [46].

VOC calculation of Sample 2 (equation 1) according to Guidelines for Surface Coating Calculation by the United States Environmental Protection Agency [47]

1 kg/L = 8.3454 lb/gal (conversion factor)

So, Density=0.9529 kg/L×8.3454 lb/gal

$$\text{VOC Content (lb/gal)} = \text{Density (lb/gal)} \times (1 - (\text{Solid Content \%} / 100)) \quad (1)$$

VOC Content (lb/gal) = 7.9507 lb/gal×(1−0.5548)

VOC Content (lb/gal) = 7.9507 lb/gal×0.44527.9507

VOC Content (lb/gal) = 3.541 lb/gal

Subpart D of Part 59-Volatile Organic Compound (VOC), Content Limits for Architectural Coatings states that the permissible Voc limit per gallon is 3.8 lb/gal. Hence, the novel varnish is in the range. Volatile Organic Compounds (VOCs) emitted from biodegradable organic components are generally considered less toxic than those from synthetic or industrial sources [48]. Natural VOCs demonstratea comparatively moderate toxicological profile characterized by:

- Reduced chemical complexity and lower xenobiotic potential
- Molecular structures are more readily recognized and metabolized by biological systems

Evolutionary co-adaptation with biological organisms, suggesting enhanced metabolic compatibility

The biodegradation potential of natural VOCs represents a critical differentiating factor in their environmental and toxicological assessment. These compounds exhibit:

- Accelerated metabolic breakdown rates
- Rapid transformation into biologically inert or less harmful metabolites
- Minimized persistent environmental contamination compared to synthetic counterparts

These naturally derived compounds demonstrate reduced toxicity primarily due to their biochemical origin, more readily metabolizable molecular structures, and accelerated environmental degradation rates. While inherently less harmful, natural VOCs require a comprehensive scientific assessment to understand their potential concentration-dependent effects, metabolic interactions, and ecological implications. The comparative analysis reveals that biodegradable VOCs typically possess enhanced enzymatic processability, shorter environmental persistence, and lower xenobiotic potential than industrial-sourced VOCs. However, researchers emphasize the importance of individual compound evaluation, recognizing that even natural VOCs can present toxicological risks if not appropriately characterized and managed [49, 50].

3.2. Carbon footprint calculation

The Carbon Footprint (CF) metric has emerged as a prominent indicator of environmental sustainability in recent years [51]. This measurement quantifies the aggregate greenhouse gas (GHG) emissions, encompassing direct and indirect sources associated with specific activities or a product's complete life cycle. The CF framework is a valuable analytical tool for identifying critical environmental impact points and evaluating potential mitigation strategies and efficiency improvements [51, 52].

This study analyzes the following unit of analysis, also known as "functional units," in the Life Cycle Assessment (LCA).

- Production of 1000 liters of paint

The functional unit estimates the carbon footprint associated with paint production. The pre-defined functional unit produces 1000 liters of paint. The system boundary defined in this analysis spans from "cradle to gate," encompassing both the manufacture of raw materials and the production of the paints. The methodology used to calculate the carbon footprint of the paint industry adheres to the GHG Protocol Corporate Standard [53]. The following steps were considered to establish the GHG inventory for the paint industry. The operational boundaries were defined in line with the GHG Protocol guidelines, taking into account the following two 'Scopes' for the study:

- Scope 1: Direct GHG emissions
- Scope 2: Indirect GHG emissions

This study utilized the latest version of the CCalC2 software for carbon footprint calculations. CCaLC is a carbon footprinting tool that estimates life cycle greenhouse gas emissions across entire supply chains. Adhering to the LCA methodology outlined by ISO 14044 and PAS2050 helps identify carbon 'hot spots' and opportunities for carbon reduction. The software features two extensive databases—CCaLC (2007-2024) and Ecoinvent (2007)—containing over 4,000 data points for various materials, energy sources, transport options, packaging, and waste management choices.

3.2.1. Paint composition

The composition of the coating studied is shown in Table 3. The table provides a breakdown of the materials used and their proportions in the coating formulation considering the functional unit of 1000 liters. Understanding this composition is essential for assessing the performance and environmental impact of the coating.

The system boundary encompasses all stages from 'cradle to gate.' Table 4 of the inventory was created based on this boundary to facilitate the carbon footprint calculation based on the CCaLC database and real-world application-oriented quantity estimation. This approach ensured that all relevant inputs and outputs were considered, comprehensively assessing the environmental impact.

Table 3: Coating composition.

Ingredient	Amount (Kg/f.u.)
Dorana oil	720
Ethanol	158
Haldummla	40
Pine gum	40

Table 4: Environmental impact data for paint manufacturing: raw materials, energy, and packaging.

Category	Item	Amount (per f.u.)	Unit	CO_2 eq. per unit	Total CO_2 eq. (kg/f.u.)	Database Section
Raw Materials	Haldummala	40	kg	1.90	76	CCaLC/materials
	Pine gum	40	kg	3.79	152	CCaLC/materials
	Ethanol	158	kg	1.70	269	CCaLC/materials
	Dorana oil	720	kg	0.589	424	CCaLC/materials
Total					992	
Energy	Electricity (low voltage) - UK	1.44	MJ	0.186	0.268	CCaLC/Energy
Total					0.268	
Packaging	Glass bottle - 10 re-uses	10.00	kg	0.188	N/A	CCaLC/Packaging
Total					0.00	
Waste	Incineration-biodegradable	1.00	kg	0.049	0.049	CCaLC/Waste
Total					0.049	

3.2.2. Process of carbon footprint analysis

The carbon footprint calculation for 1000 litres of paint using a cradle-to-gate Life Cycle Assessment (LCA) approach was based on the inventory data provided in Tables 3 and 4.

Both primary and secondary data were utilized for a comprehensive carbon footprint calculation. The concentrations of all GHGs were already converted into CO_2e figures, which were then summed to give the total carbon footprint expressed as CO_2e. The CcalC software was used to calculate the carbon footprint as follows:

a. Greenhouse gas emissions were obtained by multiplying the activity data by the emission factor for the activity, resulting in GHG emissions per functional unit of the product.

b. The GHG emissions data were then converted into CO_2 emissions by applying the relevant global warming potential (GWP) factor to the individual figures.

The present study made several exclusions due to uncertainty concerns and because it does not aim to calculate the carbon footprint through a life cycle assessment of the industrial unit. Instead, it focuses on measuring the carbon footprint of the final product within the previously defined physical boundaries.

The following activities are excluded from the system boundaries:

a. Direct emissions from fugitive and process sources are due to significant uncertainty.

b. The recycling phase, owing to its high level of uncertainty.

c. Carbon Sequestration: While some LCA studies include sequestration (e.g., forest carbon storage), it was excluded as it is too speculative or uncertain.

d. Land use changes

e. Auxiliary Materials and Services: Minor auxiliary materials (e.g., cleaning agents, maintenance services) or outsourced activities

After processing the data, Figure 6 displays the kg CO_2 equivalent per functional unit for the raw material, production, and transportation stages.

Figure 6 illustrates the cumulative emissions associated with each phase of the product's lifecycle, highlighting the relative contribution of each stage to the total carbon footprint. The carbon footprint of novel natural surface coating showed a 1210.40 kgCO_2eq per functional unit.

For a better analysis, Figure 7 shows a comparative analysis of natural surface coating with the commercially available solvent-based coating, highlighting the key sustainability benefits of the former. The CF of the commercially available coating was developed from the CcalC data and studies [52, 53, 54]. Notably, the natural surface coating demonstrates a 67.9 % reduction in carbon emissions during the raw material phase (920 kg CO_2 eq vs. 2867 kg CO_2 eq), likely due to eco-friendly and locally sourced materials. This significant improvement aligns with the principles of sustainable resource utilization. In the production phase, the carbon footprint of both coatings is similar, with only a marginal difference (approximately 5 % lower for the natural coating). Transport emissions remain negligible and identical for both coatings, indicating that transportation minimally impacts their overall environmental performance. Overall, the total carbon footprint of the natural coating (1210 kg CO_2 eq) is 61.9 % lower than its commercial counterpart (3180 kg CO_2 eq), underscoring its potential as a more sustainable alternative. These findings emphasize the importance of adopting environmentally friendly practices throughout product lifecycles to mitigate greenhouse gas emissions effectively.

3.3. Sustainability analysis: limitations and challenges

With growing concerns about environmental sustainability, diminishing fossil fuel resources, and the demands of modern industrial production, there is a pressing need to develop eco-friendly, sustainable, and bio-based coatings [55]. Strategies such as self-assembly, nano-filling, and multi-networking offer innovative approaches to further enhance and diversify the functionality of bio-based coating materials. For instance, according to the study [56], synergistic modification using nanospheres and Sulfhydrylated nanotubes through multi-networking and nano-filling improved the adhesivity of bio-based coatings by 47.0 %, increased water resistance by 9 %, and reduced viscosity to an acceptable range. Biomaterials often self-assemble from basic structural units (molecules, nano/micron particles, or larger-scale components) into multifunctional materials characterized by stiffness, strength, toughness, and other unique properties [55]. Bio-based coatings prepared using an organic-inorganic enhancement strategy demonstrated improved shear strength and water resistance, underscoring the potential of natural organic-inorganic hybrid structures as a green, sustainable solution [55]. Cross-linking agents, including specific biopolymers, can enhance coatings' cohesion and chemical resistance [57].

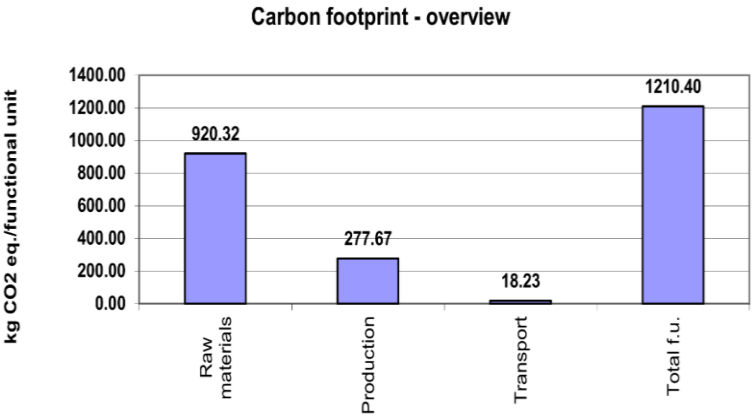

Figure 6: Carbon footprint – overview.

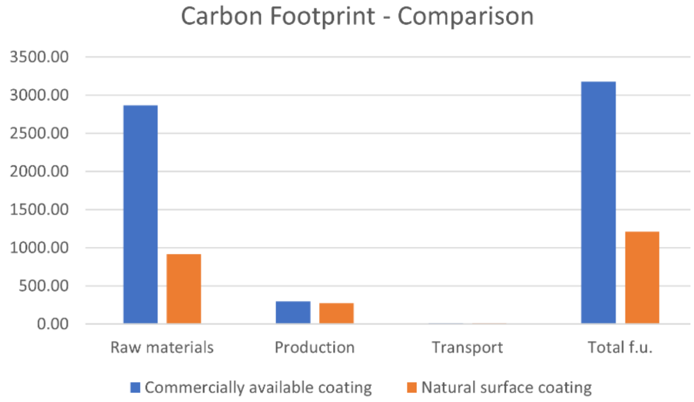

Figure 7: Carbon footprint comparison (commercially available coating vs. natural Surface Coating).

Hybrid material systems, which integrate traditional coatings with modern polymeric or bio-based materials like polyvinyl alcohol (PVA) or chitosan, have shown improved mechanical strength and barrier properties [57]. These hybrids offer a promising approach to overcoming the limitations of traditional coatings while preserving their environmental advantages. Inspired by these principles, reinforcement techniques, including cross-linking agents and hybrid material testing, could be proposed further to enhance the resilience of the current coating formulation.

While current coatings in literature offer numerous benefits, there is a growing concern regarding their environmental impact, particularly regarding sustainability and the potential leaching of chemicals into the soil or water systems. Balancing performance with ecological safety remains a critical challenge in developing these materials. Table 5 shows a comparison of coatings available in the literature.

Due to the limited literature on performance criteria for coatings specifically designed for clay-based surfaces, a comprehensive comparison is challenging. However, concerns have been identified regarding the environmental impact of coatings, particularly sustainability and the potential leaching of chemicals. The novel coating developed in this study, which consists of ethanol, pine gum, Haldummala, and Dorana oil, is made from natural raw materials. The QUV test results indicated that natural and commercial coatings experienced similar gloss reductions. Both coatings retained over 80% of their initial gloss after prolonged UV exposure, demonstrating strong resistance to UV degradation, which supports the durability of the novel coating.

Furthermore, the formulation met the permissible content of VOC. A carbon footprint analysis revealed that the natural coating was 61.9 % lower than the commercial coating. This significant reduction underscores the potential of natural coatings as more sustainable alternatives to conventional options. Thus, when considering sustainability, the overall performance of the novel coating is important.

Additionally, expanding the research scope to test other clay types and varying environmental conditions could broaden the applicability of bio-based coatings. To improve the generalizability of the findings, it is proposed to extend the study to encompass a diverse range of clay types with varying mineralogical compositions, such as kaolinite, montmorillonite, and illite [67]. These clays' distinct structural and chemical properties can significantly influence adsorption behavior, interfacial interactions, and the overall performance of the coatings [67]. Investigating these variations will enable a more detailed understanding of the underlying mechanisms and comprehensively evaluate the coatings' potential across different material systems.

Table 5: Comparison of coatings available in the literature.

Coating Type	Advantages	Disadvantages	Reference
Engobe Coatings	Can increase the durability of construction products by 30-35%. Low water absorption rates, typically around 3-6% after thermal treatment. Can be used to achieve decorative effects.	Concerns about the sustainability of raw materials as natural supplies deplete.	[58, 59]
Polymeric Coatings	Superhydrophobic coatings exhibit excellent wear resistance, low water adhesion, and self-cleaning properties. Biopolymers are eco-friendly alternatives to traditional binders like cement. Biopolymer-based treatments are non-toxic and reduce secondary pollution.	Challenges remain in their field application and long-term performance.	[60-63]
Hybrid Coatings	Hybrid composites enhance water retention and cation exchange capacity. Improved corrosion resistance and antimicrobial properties. Significantly reduce water absorption in clay bricks. Improve mechanical strength and chemical inertness.	Concerns about their environmental impact, particularly in terms of sustainability and potential leaching of chemicals.	[64-66]

The growing emphasis on sustainable development has spurred interest in utilizing locally available materials for construction. Sustainable construction involves leveraging readily accessible building materials that are low in carbon emissions, reusable, recyclable, and often sourced on-site or from nearby areas to minimize transportation costs. Incorporating traditional building materials aligns well with these principles due to their availability and renewable nature [68]. However, many traditional materials lack standardization, posing challenges in ensuring consistent performance [69]. Integrating novel coatings, such as the one proposed in this study, can address these challenges by enhancing traditional materials' durability and overall performance. This approach allows practitioners and builders to preserve traditional materials' ecological and cultural benefits while improving their suitability for contemporary applications. Furthermore, by using locally sourced materials in conjunction with advanced coatings, the environmental impact of buildings can be significantly reduced across their lifecycle, contributing to more sustainable and resilient construction practices.

Several key areas warrant further investigation to ensure the effective integration of these coatings into modern construction practices. First, the compatibility of these coatings with contemporary construction materials, such as concrete and masonry, should be rigorously studied to evaluate their interactions and bonding properties. Conducting a comprehensive cost-benefit analysis that compares traditional coatings with modern alternatives will provide valuable insights into their economic feasibility, especially in regions prioritizing sustainable practices. Additionally, implementing training programs and capacity-building initiatives for practitioners will be essential to promote proper application techniques and maximize the coatings' potential. Future research should also focus on adapting these coatings to local environmental conditions, cultural traditions, and regionally available building materials, ensuring their relevance and effectiveness across diverse settings. Addressing these aspects will improve the practical application of traditional coatings and foster their broader adoption within modern, sustainable construction workflows.

4. Conclusion

This research formulated a new coating solution for clay-based surfaces, filling a void in the literature for coatings particular to clay-based materials. Materials such as pine gum, Haldummala, Dorana oil, and ethanol were used based on traditional Sri Lankan coating techniques. A study with 15 samples of varying Haldummala concentrations found that Sample 2, with a concentration of 4 g/L, performed best regarding solid content, density, optical properties, viscosity, and gloss. This sample had a density of 0.9529 kg/L, solid content of 55.48% by mass, viscosity of 21 seconds, opacity of 10.48%, and gloss value of 33.5 units at 60°. After 500 hours of artificial aging using QUV test cycles, there were no signs of peeling, cracking, or blistering. The QUV test showed similar gloss reductions for natural and commercial coatings, ranging from 9 to 12 %. Natural coatings had gloss reductions of 9.46, 12.9, and 10.02 %, while commercial coatings showed reductions of 9.19, 12, and 11.25 %. Both types retained over 80 % of their initial gloss, demonstrating strong UV resistance. The formulation complied with the VOC limit of 3.5 lb/gal. The carbon footprint analysis revealed that the natural coating emitted 1210 kg CO_2-equivalent, which is 61.9% lower than the 3180 kg CO_2-equivalent of the commercial coating. This highlights the sustainability of natural coatings as an alternative to conventional ones. Compared to commercially available multifunctional coatings, the new coating formulation performs well and could be sustainable for clay-based surfaces. Further research should evaluate its stability in field conditions and its broader applicability.

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