

## A Review of High Stability of Fade-resistant Dyes for Long-Lasting Paints

Maryam Wahid

Department of Chemistry, University of Agriculture Faisalabad, Pakistan

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### Abstract

Traditional paints are exposed to harsh environmental influences like UV rays, oxygen, and water, which cause photodegradation of the pigments' colors. This review aims to discuss current research endeavors that could improve the durability of paints in the real-world applications of painting to achieve the desired colorfastness properties. It has become evident that recent research activities indicate that it is not only the chemical structure of organic molecular dye that is important for determining the stability of colors but also their interactions with their binder material systems. Only high-quality pigments with sensitive organic dyes require sophisticated applications from UV Absorbers and Hindered Amine Light Stabilizers (HALS) to ensure some acceptable stability. It explains clearly that UV light triggers the production of free radicals that contribute to the destruction of dye color pigments. Moreover, both laboratory-based research work by this paper intends to discuss the effective contributions of nanotechnology in the study of durability. Moreover, it briefly focuses on Nano Dyes and Nano-Encapsulated Colors. Due to their immensely large, exposed surface area, the ingoing UV rays are effectively reflected by the Nanostructure of the tiny particles. This paper intends to clarify the negatively reacting inorganic additives of the Nanostructure, such as Titanium Dioxide (TiO<sub>2</sub>) and Zinc Oxide (Zn-O), which work as photo-catalysts in such outdoor paints. At Nanoscale we use Graphene Nano plates and other two-dimensional materials which act as a protective barrier against the fading of paints.

**Keywords:** fade resistance dyes, photodegradation, photo-catalysis, Zn-O, TiO<sub>2</sub>, Sustain- ability

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### 1. Introduction

Pakistan's paints and coatings sector offers a very rewarding investment avenue, particularly for US firms, since most of the potential lies in the upstream and downstream subsectors of the industry. The sector is currently estimated at about US\$400 million and is projected to grow at an annual growth rate of 4 percent during the next four to five years. The paint industry in Pakistan is highly diversified and produces a wide range of finished and semi-finished products, including pigments, distempers, plastic emulsions, enamels, undercoats, primers, rubber paints, aircraft paints, marine paints, anti-corrosive and anti-fouling paints [1]. The artificial dyes are considered the backbone of various present days industries due to their very intense color and low cost of preparation. Recent research has also explored their pharmaceutical applications. This industrial success has come with developing damage to human health and the environment. Workers exposed during the manufacturing and application of dyes are prone to skin and respiratory diseases and, upon chronic exposure, their hormones are disrupted. Certain azo dyes pose greater concern because their cleavage can release aromatic amines that are carcinogenic and endocrine disrupting even though they are widely used around the globe

[2]. While the use of synthetic dyes is very helpful, producing large-scale industrial utilization, especially in azo dyes, creates large chemical wastes and significantly enhances environmental pollution. Pigments constitute a vital basis in determining the type of paint and the appearance of paint [2]. The final color and opacity are mainly affected by pigments, while some forms of pigments help to thicken and boost color.

Commonly used pigments include carbon black, earth colors, ultramarines, and others. Paints are enhanced with additives to offer improved basic properties, such as slip resistance, fire resistance, and resistance to ultraviolet rays, or to prevent defects like foaming, leveling, flocculation, and settling. Basically, there exist many types of paints; among the well-known ones are PVA latex paints, acrylic paints, silicate paints, and lime-based paints. Basically, each paint contains basic components, which include fixed medium, volatile medium, pigments, fillers, and additives [3]. PVA latex paints are based on polyvinyl acetate and possess lower adhesion, lower durability, and lower resistance to water and alkaline surface than acrylic paints, so they are mainly used inside buildings. Large-scale deteriorations of paint are the common problems as it is not a permanent solution [4]. After drying, the total thickness of paint

usually stays about 40 to 50 microns by applying two to three layers. The metallic paint is otherwise known as polychromatic paint. These colors can be made much brighter and brilliant by changing their type, number, size, and color of metal particles [5]. Changes would thereby affect the paint's shine, its visual impact, and its reflective light capability. About 60% of world dyes are consumed by the textile industries due to the ever-increasing demand for long-lasting, brighter colors with every passing season of fashion. This growth, however, has created tremendous environmental problems. Today, the textile industry is rated as the second leading cause of water pollution worldwide, behind the leather industry (Table 1) [6].

## 2. Natural Dyes and Pigments

For sustainable paintings, one of the areas that researchers often become involved with is natural dyes, or pigments that originate from plants, animals, or microbes. Some of the classic natural dyes that were originally produced through complex processing routes include carmine, red, originally sourced from the cochineal insect *Dactylocopus* and the famous Tyrian purple, originally sourced from certain sea snails such as *Murex brandaris*. In addition to such classical natural dyes, one of the more interesting alternatives that have arisen more recently is microbial dyes or pigments, originally sourced from microbes such as bacteria, fungi, and algae [7]. Some of the examples of such dyes include prodigiosin originally sourced from *Serratia marcescens* bacteria, as well as fungal indigo originally sourced from the algae species *Saccharothrix azulens* [8]. The importance of such microbial dyes as alternatives for this review is that they provide one of the more effective alternatives that are both biodegradable and environmentally friendly in contrast to petroleum-based synthetic dyes. One of the challenges that make such natural dyes difficult for paints that last for a long time is their poor photo-stability [9]. Hence, the aim of this review is to investigate the potential of such dyes for development through either chemical or protective means that would provide sufficient fade resistance for use in long-lasting coatings. HALs are some of the most powerful additives. Their major role is to remove harmful Free Radicals that develop in paint films. Both the polymer binder and dye that instantly trap the radical (Figure 1) [10].

## 3. Nanotechnology: A Heart of UV Protection

Nanoparticles are what make current effective UV protection possible. These tiny particles provide significantly better effectiveness in protecting against UV rays than doing more natural compounds. This is a result of their important property: their enormous surface area to volume ratio. "The biggest worry is the possibility of these inorganic compounds forming. This is what Photo-chrome describes as the damage done by the Photo-chrome damaging free radicals via oxidation caused by exposure to UV radiation, potentially damaging other organic compounds in the paint film [11]. Dye particles can be encased in a protective capsule (e.g., of silica or polymers). This prevents the dye particles from encountering direct chemical or moisture attack or atmospheric oxygen, thereby vastly prolonging their useful lifetime.

## 3.1. Inorganic Nanoparticles in Coating

### 3.1.1. Titanium Dioxide $TiO_2$

In the high stability coatings arena, there are two key inorganic nanoparticles that are very important for UV stabilization. One of these is Titanium Dioxide, which is a familiar mineral found in the form of ultra-fine nanoparticles with a diameter around. These nanoparticles tend to clump together, with the optimum sizes for reflection of UV rays between 60-120nm. To ensure that these particles disperse easily in the total paint solution,  $TiO_2$  particles are often treated with materials such as silicon oils, or  $SiO_2$  (silica), or sometimes with alumina, which is  $Al_2O_3$ . Treatment with silica would also make it more absorbent of UV radiation [12].

### 3.1.2. Zinc Oxide Zn-O

Zinc Oxide: It is another mineral that is often processed into a particle form with optimum size measuring between 20-30nm. It is normally protected with silicon oils,  $SiO_2$ ,  $Al_2O_3$  for stability purposes in the chemical. It is often regarded as a better UV blocker given that it is more transparent (leaving less white residue) with more coverage, especially in the UVA rays with longer wavelengths [13]. The major issue would be the possibility of these inorganic compounds causing the production of harmful free radicals via oxidation upon exposure to UV rays, which could pose a potential threat to other organic compounds present in the paint film [14].

## 4. Photochemistry of Dyes

A molecule of Colorants interacts with light in complex ways. When a dye molecule or a pigment absorbs a photon of light, it becomes exciting. This is because it gains energy. As a result, it jumps into an exciting state. This molecule is left with excess energy, which it can release through different means. It loses excess energy and softly returns to its normal state. It undergoes a photochemical reaction that allows it to break down, resulting in the formation of new compounds that are often colorless. This is the process responsible for fading of color [15]. There are two major classes of photochemical reactions that produce fading of dyes' colors. In this type of photochemical reaction, the dye itself absorbs the photon and gets into an excited state.

### 4.1. Direct Photochemical Reactions

When the dye molecule itself absorbs a photon to get energized or enters into a photo-exciting state, it must look for an escape channel to remove that extra energy. It has various options, some of which could be safe, while some could be destructive. It could remove the extra energy by Releasing the energy in the form of a new photon of light called Fluorescence or Phosphorescence [31]. If it doesn't choose the safe option, it enters a photoreaction, causing loss of color photodegradation. This occurs in two ways: An excited dye molecule is not stable on its own. It decomposes without any reaction with another material in paint system. This decay takes place through internal chemical reactions such as dissociation, self-structure rearrangement, or internal reduction-oxidation reactions. An excited dye molecule, with high degree of instability, reacts with other materials that are present in surrounding environment (e.g., binder, solvent, or impurities). In both self-destruction and

reaction with other molecules, same effect is achieved: structure of dye molecules changed, causing color to fade.

#### 4.2. Indirect Photochemical Reactions

Sometimes, the damage to the color is not caused by the direct effect of the photosensitizer exposure to light, but by an intermediary, called Photosensitizers. These compounds are very effective. This is shown by their large absorption coefficients; that is, they absorb light easily. Their activation energy is low; therefore, they can become available to react once they are excited.[15] [31] These compounds are usually found in the same layer as the dye or pigment that you are studying. When a photosensitizer is excited, it damages the dye through the following two mechanisms: A photosensitizer molecule, after becoming excited by energy from light, can react with a nearby dye or pigment molecule. More generally, it reacts with ordinary molecular oxygen, which is present in the air, to produce a highly reactive form called Singlet Oxygen. This singlet oxygen is then the reactive agent that attacks and decomposes dye molecules. An interesting feature is that dyes themselves can be photosensitizers. This is because they too can be excited to produce singlet oxygen, which then attacks other dye molecules. Examples of such dyes include Green 8 (pyrene dye), Chlorophyllin, Red 22 (xanthene dye), and Green 5 (anthraquinone dye) (Figure 2) [16].

### 5. Photo- Degradation of Dyes

Photodegradation is the process that takes place with the degradation of the colorant in the presence of sunlight, contributing to loss of the material's color. This is a dynamic process that depends on certain factors determining the lifetime of the material's color.

#### 5.1. Internal Factors

Internal characteristics are properties of colorant itself, basically chemical structure of the dye or pigment.

##### 5.1.1. Chemical Structure

This is the basic structure that contributes to the inherent resistance of the colorant to UV rays.

##### 5.1.2. Physical State

This comprises the absorption of the colorant to light (absorption spectrum) and polarity.

#### 5.2. External Factors

Second, there are external factors which are conditions outside of colorant that interact with layer of paint.

##### 5.2.1. Light Characteristics

This refers to wavelengths emanating from light source. Environmental Exposure: Presence or absence of oxygen, temperature, humidity, and PH of environment.

##### 5.2.2. Solvent Type

This refers to type of material that dye is blended with, for example, type of solvent found in paint.

#### 5.3. Role of Light Intensity

Light intensity affects the light stability of coloring matters and is generally evaluated under strong, accelerated lighting conditions in a laboratory. Contrary

to intuition, the effect of the intensity of the illumination source is unexpectedly complex: Usually, the higher the light intensity, the faster the fading, as more energy (photons) is added to the system. A quantification of this is achieved through a unit of measurement called quantum yield. It basically states the chances that an amount of light being absorbed by the material. Nevertheless, there is no straightforward relationship between the fading of a dye and the extent of the light of the incident. Some literature (research into the mono-azo dye Reactive Blue 13) indicates that the brighter the incident light, the proportionally faster the fading rate increases. Moreover, other research works revealed that for some organic dyes, extent of fading rate increase could be drastically random, with the extent of fading rate increase potentially small or an astonishing 240-fold increase [16].

#### 5.3. Time

This is entirely logical—and what happens is that the longer the painted surface or the colored material is exposed to the elements, the more damage to color there will be. As a result, scientists do not wait for years to observe what happens. Instead, they make use of artificial aging tests, where they expose the colors to very bright lighting for a short time to predict what exactly will happen to the likely long-term effect of the coloring after a long time in the real world. The more you expose your coloring to the elements, the shorter its life span. To obtain fast results, researchers employ an instrument called a Micro fading Tester (MFT) [17]. Questions about the validity of the MFT test results. In the case of most durable-colored pigments, the Reciprocity Principle is valid. In contrast, for weaker organic pigments (such as those of Pomegranate or Turmeric), Reciprocity Principle” is invalid for high light intensity. This indicates that for weak pigments, employing a high-intensity source of light can produce a test result that is unrealistically low for material's actual lifetime. To produce a more accurate test outcome for sensitive pigments to lighting, testing must be carried out using lower levels of lighting that better resemble real conditions [18].

#### 5.4. Wavelength

It is important to state that the color or wavelength of the incident light is crucial in the degradation process too. A shorter-wavelength light (in the UV range) possesses more energy and is often sufficient to break the chemical bonds of the colorants, thereby proceeding at a quicker rate of degradation. It is, however, important to note that even though UV is more powerful, some photo-unstable colorants tend to degrade more quickly by Visible (Vis) Light, with only the more photo-stable colorants requiring the potency of UV Light to degrade. A colorant must absorb the incident light in order to undergo degradation. If the pigment with higher absorbency is in the Visible range of light instead of the UV range, it means that it would degrade more quickly through Visible Light, despite latter being less powerful. This helps clarify the fact that some colorants would degrade more quickly through Light of longer wavelengths if that wavelength were perfectly matched with its absorbency. Chemical bonds of colorants are determined by their molecular structure. A study reveals that Azo dyes absorb more Visible Light of spectrum, whereas

Phthalocyanines predominantly absorb more UV Light of spectrum [19].

### 5.5. Concentration of Dyes and Fade Resistance characteristics of Dyes

The amount of pigment or organic dye in the coating is one of the major factors that determine the effectiveness of the fading resistance of the color. Research indicates that with an increase in the amount of organic colorant in the coating (which results in dark shades), the rate of photo-degradation decreases. This is attributed by aggregation. Higher concentration of the dye or pigments results in the dye or pigments aggregating into larger clusters. The larger clusters result in a reduced ratio of surface area that is exposed to factors such as light and oxygen, which results in very low fading. Research proves that for lighter and dark shades, the percentage of loss of the colorant by photodegradation is higher for the latter shades. In the light shades, colorants are isolated in the paint film resulting in availability of the colorants entirely to light. Although fading is inevitable with regard to concentration, dark shades of paint provide better durability since a higher concentration leads to formation of clusters. This is one of major factors that determine maximum stabilization of coloring of long-lasting coatings (Figure 3) [20].

### 5.6. pH and Color Stability

Additionally, pigments with electric charges, either positive or negative, are more likely to initiate chemical reactions that make the dye molecule fade away. Therefore, molecules with electric charges are less photo-stable since they are less stable when exposed to light [21]. These dyes, such as ceramic acid, tend to fade away quickly if exposed to an alkaline solution where they become negatively charged. On the other hand, basic dyes such as methylene blue become less photo-stable if exposed to an acidic solution where they become positively charged. One of key considerations for maximum photo-stability is that the dye should be mixed with a chemical system that helps to ensure that the molecule does not lose its more stable state or form electric charges. A key strategy for maximizing the photo-stability of sensitive dyes or pigments is. On the other hand, basic dyes such as methylene blue become less photo-stable if exposed to acidic solution where they become positively charged. One of key considerations for maximum photo-stability is that dye should be mixed with a chemical system that helps to ensure that molecules do not lose its more stable state or form electric charges. A key strategy for maximizing photo-stability of sensitive dyes or pigments is.

## 6. Drawbacks of Conventional paints

Whether it is Large-scale failure of paint is a very common phenomenon. Painting work is not a lifetime association. After curing, the average thickness of the layers of 2-3 colors is 40-50mm. A painting work consists of it requires extensive planning, and its durability is reliant on all the factors that must be considered before painting.

### 6.1. Blistering

Vapors pressure forms beneath the dried top layer as a result of volatile material retained by the top surface

of the film peeling away too quickly. Usually, this is caused by heat of sun warming softening paint. A weakened film forms blisters due to heat expansion of vapors. Resins of wood carrying the blend of resin with coating material or moisture can also contribute to blistering formation. It is likely that wood is wet before it is dried or before painting through immersion or other means. This is independent of any of its other properties.

### 6.2. Droopy

Downhill flow is formed by applying paint to a vertical surface because of the gravitational pull. Various terms are used to denote this process, such as running, curing, and sagging [22]. A certain tolerance of this flowing is inevitable for effective leveling, but too much sagging is not acceptable [23].

### 6.3. Cracking

If the break in the paint is able to reach the substrate, then this is referred to as cracking. It indicates the presence of a failure or lack of adhesion [24]. Cracking or flaking actually caused by poor-quality paints, which could result in lack of flexibility or adhesion.

### 6.4. Flaking

“Flaking” is the term that describes the “process whereby the paint layers separate from the surface beneath and appear as flakes.” This type of “flaking is brought about by the lack of adhesion or hardness[25].

### 6.5. Wrinkling

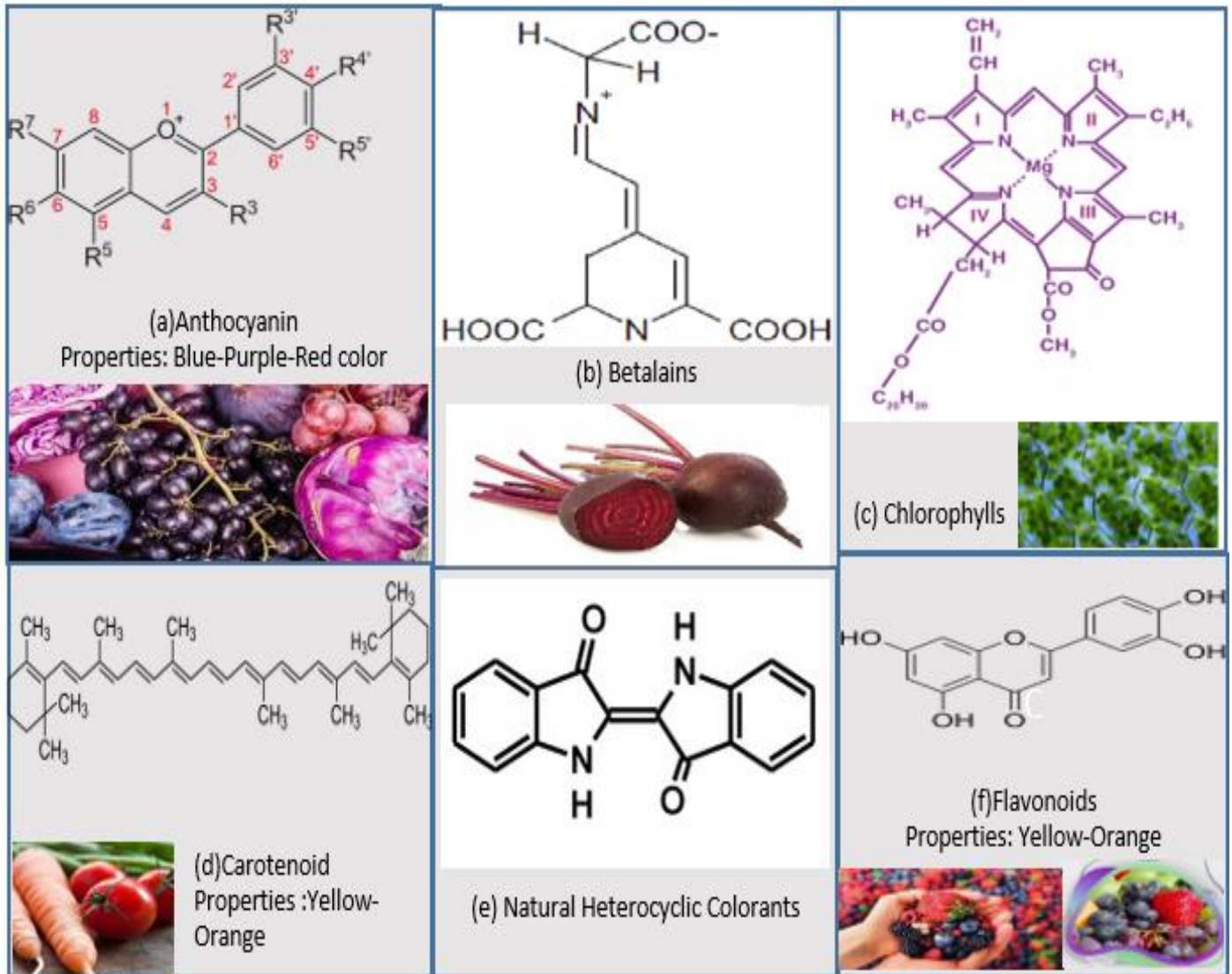
If one applies too thick a layer of the paint, which is more likely to happen with alkyds or oil-based paints, the paint dries before the other layer is cured. This is what creates wrinkles in paint or texture[25]. Applying paint on a scorching day means that the topcoat of the paint dries before the other coat cured. This also happens if one lives in an area that is either warm or wet, since other coat takes longer to dry and is set before other one is cured [26].

### 6.6. Fading

When painted materials are left exposed to direct sunlight for a prolonged period of time or even for good, such as outdoor house paints, they are faced with a very big task. This is because the sun’s strong ultraviolet rays are very powerful, with the capability of causing a significant amount of damage to the pigments of the color. This is always likely to happen since painting is exposed to direct sunlight. This means that the sun is attacking the color right on your painting’s surface [27].

### 6.7. Alkali

Naturally found lime or calcium hydroxide in the walls starts reacting with the carbon dioxide gas present in the air. This chemical reaction increases the pH of the surface of the walls. This causes an increase in alkalinity. This is difficult for painting films. It basically decreases the integrity of the painted layer. It affects the stability of the paint. It also affects its ability to adhere to the walls. This contributes to early loss of color and the surface [28].



**Figure 1.** Various types of natural dyes and pigments are classified based on chemical structures.

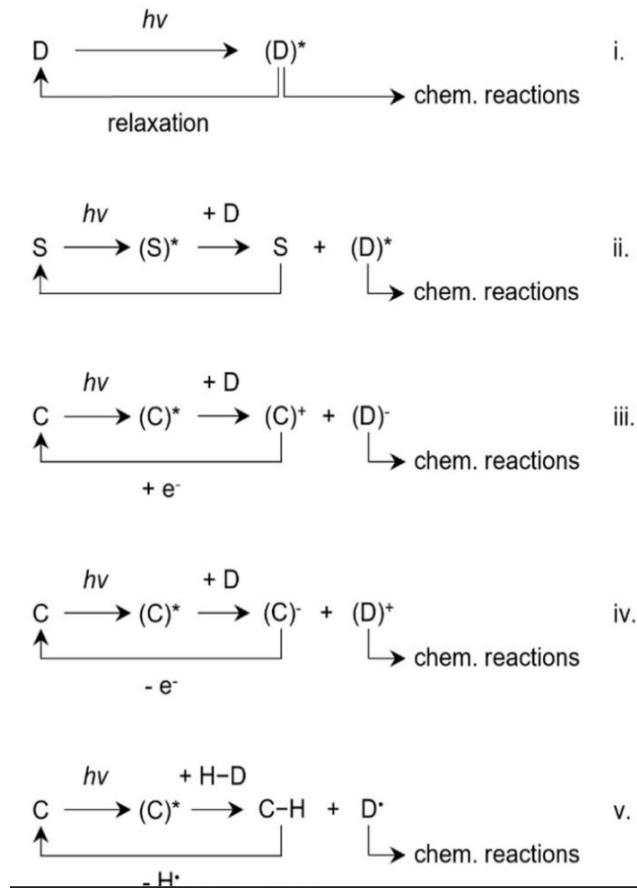


Figure 2. An overview of direct and indirect photo-chemical reaction

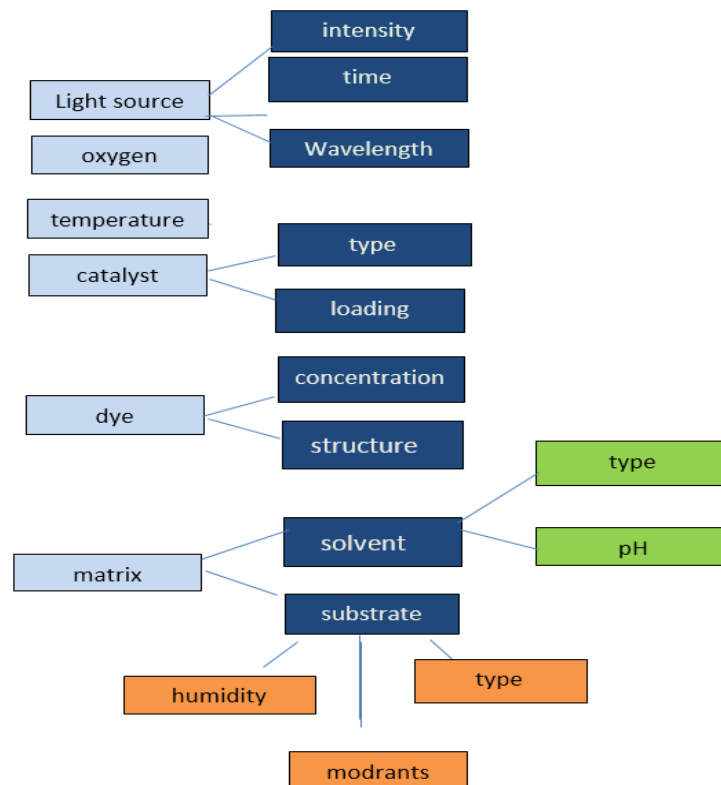


Figure 3. Overview and classification of discussed parameters that influenced the photo degradation of dyes

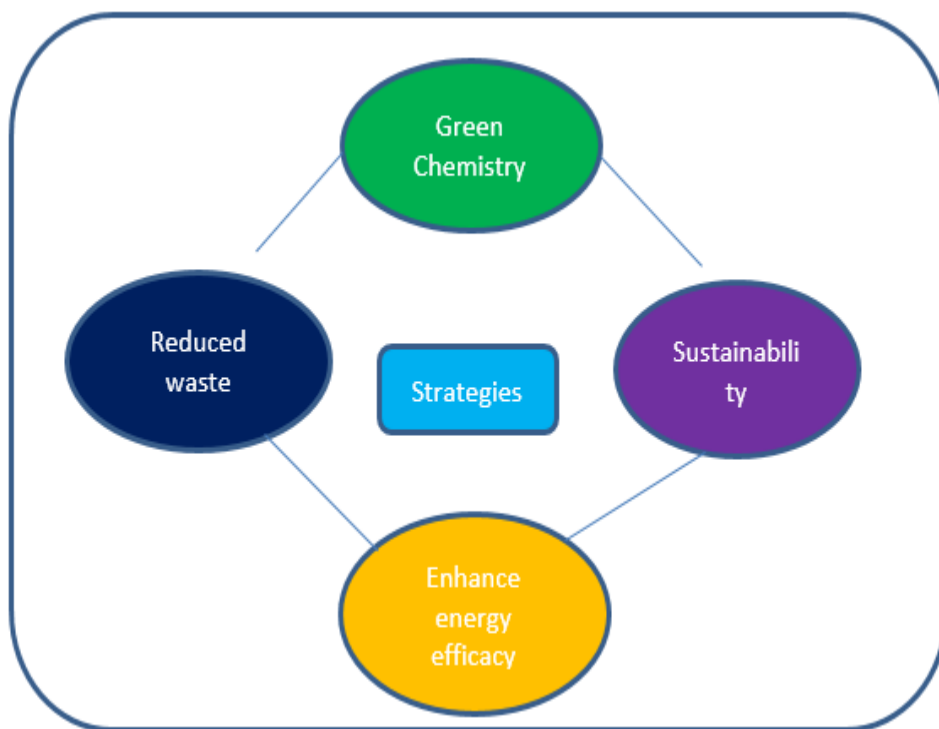


Figure 4. Advantages to make paint ecofriendly

Table 1. Different components of paint

S. No	Ingredients	Properties	Examples
1	Extender	Provide Bulk to Paints	Red lead, zinc oxide, lithopone, calcium carbonate
2	Pigment	Provide color protection	Zinc yellow, Titanium dioxide TiO <sub>2</sub> , Zinc Oxide Zn-O, Carbon Black, Chrome oxide green
3	Binder	Good Adhesion	Alkyl resins, acrylic resins, chlorinated rubber Latex (PVA) etc.
4	Paint thinner	Medium for dispersion	White spirit made of mineral turpentine, water Xylene, Toluene and other substances
5	Driers	Quick drying of paints	Salts of Calcium, zirconium, barium, cobalt, zinc,
6	Additives	Modified the paint properties	Plasticizers, fungicides, insecticides, biocides Deformers, emulsifiers, UV stabilizers

7. Advantages to make paint is Ecofriendly

Currently, issues related to sustainability in the environment have become a significant environmental issue since sustainable painting is obtainable from renewable or recycled materials that reduce the environmental concerns by using eco-friendly paints.

7.1. Green Chemistry

The coatings industry is aggressively searching for “green chemistry” solutions to address the issue of high VOC emissions. This is achieved by a series of strategic material changes in some of these products. Firstly, there is emphasis on finding alternatives from renewable material procurements, moving entirely away from fossil fuel-based products. This is achieved by using other materials such as linseed or rapeseed oil to produce major components such as coils of deoxidized fatty acids [29]. Notably, such a shift must not come at the cost of reduced effectiveness. This

means that through production, products such as new VOC-reducing adhesion-promoting chemicals must retain critical properties of the original. Such new advancements even extend to other special products, ensuring that antifouling paints for boats made with water-based products, for example, not only minimize VOCs but also minimize the need for maintenance [30]. Secondly, application efficiency is important for VOC reduction. Due to advancements in the production of pigments and organic coloring, a final finish is achieved through just one application coat of the VOC-containing material, unlike earlier applications that ranged between three to four before the desired finish could be achieved [31]. While the U.S. is dependent on soy-based resources, the aim for the total European community is to improve feedstock chemistry to reduce petroleum dependence and carbon footprint [32].

- Carbon-based Graphene enhanced paints effectiveness it is cost effective method and high thermal stability, scalability and resistivity. Graphene not only protects the color of the paint but also prevent morphological defects on the surface of the paints. In future we focuses on the materials for formation of dyes that makes paints cost effective and sustainable[42].

### 7.2. Sustainable Production Coating

Traditional methods of painting production and disposal of such paints often pose a great risk to the natural environment through waste production, the emission of toxic chemicals, and the subsequent contribution to landfill waste. However, the tide is gradually shifting towards more environmentally sustainable alternatives that offer substantial improvements over previous approaches. These sustainable paints are often VOC-free (Volatile Organic Compounds) or do not contain toxic chemicals, with their raw materials extracted through eco-friendly production processes that practice waste reduction and minimize environmental pollution [33]. A great example of such sustainable alternatives is the recent resurgence in the use of water-based paints that use water as their active solvent, ensuring that they are much easier to clean up without causing any environmental damage through petrochemical-based paints cleanliness that is often hazardous by virtue of being oil-based in production [34]. A great example of innovative alternatives is the advent of the 'power coat' that is applied in its dried powder form before being baked into hardened durability long enough to produce a very durable finish that is more robust compared to other similar alternatives since it contains many less VOCs that would otherwise result in certain detrimental by-products with a considerable amount of hazardous waste left behind in the production process of other paints through abundant marketing [35].

### 7.3. Improve Energy Efficiency

It increasing overall sustainability by decreasing energy consumption, less cost, lowering minimize greenhouse gases [36]. The management of hazardous waste is a long-standing critical issue that the paint and coating industry has faced. A great amount of progress has been achieved, especially with respect to waste prevention and the principles of circular economy practices. This is evident with the increasing adoption of the practice of collecting and recycling leftover paints. Additionally, the American Coatings [37]. Association states that an astonishing 97% of waste solvents is actually recycled for any subsequent use from manufacturing sites. This is a clear demonstration of their effort to minimize frequent production of hazardous waste products. Moreover, besides the practice of recycling waste products, the industry is also engaged in practices of waste prevention. This is achieved through the utilization of simple electronic calculator devices by consumer and construction clients to establish the exact requirement of paints for any given task, thereby effectively avoiding any waste or deformation issues altogether [58]. Though the painting industry has achieved significantly better on the front of environmental accountability, still challenges lie on the horizon. Ever-advancing technological applications for paints promise an eco-friendly, more optimized, and more effective vista for a safer future. This not only owes a

significant benefit to environment but also helps in the reducing costs for economy and consumer (Figure 4) [38].

### 8. Future Prospects

"The task of developing durable paints that last for a long time is a never-ending process." Future research would be on the following three unique areas that would lay down the foundation for the next generation of paints that resist fading:

- Modern technology is aware that inorganic nanoparticles such as  $\text{TiO}_2$  or Zn-O exist duality: they are UV blockers that, exposed to light, become chemical aggressors (photo-catalysts) that damage the paint[39]. This is even more harmful to sensitive organic dyes. These days, research geared significantly toward developing "Core-Shell Nanoparticles" for not one, but for two purposes: to protect the binder, of course, but more important, to safeguard delicate dye molecules. This is achieved by encasing the UV-active core, either the Zn-O or the  $\text{TiO}_2$ , with an inert or non-reactive shell of silica or polymer materials[40] This novel approach would not only provide better UV protection, but it would also completely suppress detrimental chemical reactions that damage paint matrix as well as dye molecule structure.
- Due to environmental forces, there is a growing need for the use of natural dye colorants. These dyes tend to be more sensitive to light. Future research would focus on the development of Smart Binder Systems that can intervene at a molecular level. These binders would do more than just bind the pigments. Instead, they would be designed to protect sensitive dyes from environmental attacks by an acid or alkali, which would otherwise render these sensitive dyes electrically charged. This would ensure that the dye is as fade-resistant as possible [41].

### 9. Conclusions

This review reiterates that the issue of rendering paint completely durable with respect to coloring is complex, requiring much more than an understanding of robust pigments. It is a complex task that understanding the chemistry of dyes. It is more about the durability of sensitive dyes. Additionally, it is evident that our analysis verifies that the major risk for low longevity is the production of radicals caused by UV radiation, which is effectively blocked by the selective application of UV Absorbers and HALS. Moreover, importance of both the concentration of pigments (where black hues offer inherent protection by aggregating) and PH levels that can damage dyes by charging should not be ignored. What emerges as imperative for future is that there is a need for intelligent chemical design aimed at countering the hazards caused by photo-catalysis by inorganic nanomaterials such as Zn-O and  $\text{TiO}_2$  through inert encapsulation. Moreover, it is imperative that we look towards AI models for predicting lifespans of new dye molecules with absolute predictability without having to fall back on the tests that are currently being used. As such, with integration of above-mentioned advanced chemical methodologies or approaches, painting industry is able to adequately meet not only aesthetic needs for dye-based color retention but also need for sustainable paints in future.

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