

Advances in Color Chemistry and their Impact on the Paint Industry

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ABSTRACT

The broad topic of colour chemistry covers the manufacturing, applications, and invention of pigments and dyes, which are essential to the paint and coating, textile, and electronics industries, among others. Recent advances in colour chemistry have had a significant impact on the paint business, particularly with regard to coating sustainability, usefulness, and durability. This review sought to address how improved pigments, green chemistry solutions, and new technology could revolutionise the paint business as a result of recent advances in colour chemistry. The use of nanotechnology in the creation of nanopigments which have superior optical properties and produce vibrant, long-lasting colours that are resistant to weather is one of the other novel aspects. These advancements take into account the growing customer interest in eco-friendly products in addition to adhering to the rules governing low-VOC formulations. Technology advancements have also improved product positioning and quality through colour matching and customisation choices. We conducted a comprehensive literature review of scientific databases and reports from academic and industrial sources to gain a systematic understanding of current and upcoming trends, issues, and developments in the field of colour chemistry and the paint industry. The importance of colour chemistry in advancing the coating industry across several industries, including automotive, architecture, and consumer electronics, is expected to be increased by future developments in colour chemistry research, which are anticipated to further advance the field of material science and application methods.

Keywords: Colour chemistry, Nanopigments, Color matching, Functional coatings, Regulatory compliance

INTRODUCTION

Technological advancements in colour chemistry have been instrumental in transforming the paint industry, bringing about unexpectedly deep penetrations into several domains of demand, usage, and organisation. Continuous research into improved pigments and techniques for paint preparation and application drives this evolution, enhancing the look, functionality, and durability of paints. In summary, color chemistry focuses on understanding the creation and production of colour [1]. Scientists have combined organic colours derived from minerals and organic chemicals with nanomaterials and recently synthesised organic structures. These developments satisfy different customer and market demands while offering a greater variety of new colours and improving colour fastness and durability. Nanotechnology's use in color chemistry is one of the field's most significant advancements [2].

Nanoparticles, smaller than ordinary pigments and possessing different optical properties, facilitate the production of bright and intensely saturated colours more easily [3]. These nanoparticles' unique optical characteristics allow for nanoscale light control, resulting in color that is more brilliant, long-lasting, and resistant to chemical and UV ray deterioration. These developments meet the growing demand for long-lasting, environmentally friendly construction while also expanding the methods used in paint manufacturing. Additionally, they have adopted a number of technologies for colour matching and customisation. These days, manufacturers utilise spectrophotometers and computer programmes to generate customised programmes for specific sectors, maintain colour quality, and ensure batch uniformity. Paint manufacturers have been able to better meet market demands and handle change better because of

this capacity to optimise production processes. But color chemistry goes beyond simple technical advancements in paint; it also addresses the industry's legal and environmental issues. For instance, there is a growing need to reduce the amount of volatile organic compounds (VOCs) and other hazardous chemicals in paints since it is becoming more difficult to contaminate the environment through emission. Recent advancements in colour chemistry enable the creation of new pigments and formulations that meet strict environmental criteria while maintaining performance and colour quality. This shift towards sustainability not only aligns with corporate social responsibility agendas, but it also appeals to the consumer base, which is continuously seeking environmentally friendly items. Furthermore, we should not underestimate the impact of color chemistry on consumer purchasing patterns and marketplaces. They elicit emotions and symbolise values and customs. In order to introduce new colour

The Development of Pigments and Nanotechnology

Over time, researchers have recognized nanotechnology as the technology that fundamentally altered the efficiency and adaptability of pigments, opening up new possibilities for the study of materials science, paints, coatings, and

The Qualities and Advantages of Nanopigments

1. Colour Enhancement and Optical Characteristics: Because of their size, nanoparticles have unique optical properties that determine how they interact with light [7]. This phenomenon, known as the plasmonic effect, makes it possible to synthesise colours that are richer, more intense, and less prone to fading than those made with conventional colourants. Designers and consumers have more options because they can control the size, shape, and composition of the nanoparticles, changing pigments to provide the desired color and effect.

2. Durability and Performance: Although they are susceptible to saponification, nanopigments are well-known for their outstanding stability. They offer better defence against environmental threats such as heat, oxygen, UV radiation, and chemical attacks. Because of their exceptional durability, pigments generated from nanotechnology are well suited for outdoor use, where features such as colour fastness and permanence are crucial. For example, the use of nanotechnology in vehicle coatings helps them maintain their original gloss and colour even after prolonged exposure to harsh weather.

Utilisations in all Sectors

1. Architectural Coatings: Due to their ability to enhance color intensity, weather resistance, and durability, nanopigments are increasingly finding their way into architectural paints and coatings [9]. These coatings, unlike materials that deteriorate over

collections that would appeal to modern living and design trends, certain paint producers conducted social trend analysis and colour psychology studies. In addition to aiding in product uniqueness, this strategy helps establish brand identification in a cutthroat market. All things considered, advancements in colour chemistry are a vivid synthesis of technology application, scientific study, and commercial potential in the paint industry [4]. We anticipate further advancements in every field of study to enhance the performance, sustainability, and color intensity of pigments and coating systems. We must understand these developments as opportunities and expectations continue to transform the nature of color science across the paint supply chain, from paint manufacturers to designers and consumers. Developments as opportunities and expectations continue to transform the nature of color science across the paint supply chain, from paint manufacturers to designers and consumers [5].

related subjects [6]. This depends on the mobilisation and utilisation of nanoparticles, which are materials with a typical size range of 1 to 100 nanometers, to create pigments with properties that are just not possible for their typical counterparts.

3. Functional Enhancements: In addition to pigment particles' colour, nanoparticles enable the incorporation of functional additives into pigment particles in addition to their color [8]. It makes it possible to create multifunctional coatings with qualities like antibacterial, abrasive, conductive, magnetic, or self-cleaning layers, among others. Real-world applications, such as conductive finishes in electronics and antimicrobial finishes in healthcare, require testing these advances to enhance their functionality.

4. Accuracy and Management in Formulation: This implies that colorant manufacturers possess nanotechnology instruments to precisely modify pigment characteristics. Manufacturers can achieve a high degree of control over the size, chemical makeup, dispersibility, and agglomeration ability of the nanoparticles to achieve optimal compatibility with specific binders and application procedures. Regardless of the batch generated, this level of control aids in maintaining a fine particle distribution in the paint formulas, providing the same colour and performance.

time and require recoating, can function for months or years without exhibiting any noticeable degradation symptoms, thereby ensuring long-lasting performance and resource efficiency.

2. Automotive Finishes: The automotive industry's adoption of nanotechnology allows for high-end, polished surfaces that meet the high standards for performance and appearance of automobiles [10]. Automotive coatings that use nanopigments add remarkable shine, deep, rich color, clarity, and scratch resistance, enhancing automobile appearance and longevity.

3. Industrial and Specialty Coatings: Nanotechnology application improves the qualities of industrial coatings, including corrosion resistance,

Sustainability and Environmental Considerations Diminished Environmental Impact

1. Nanotechnology: Nanotechnology enables low-volatile organic compound (VOC) paints and coatings, improving both indoor and outdoor air quality, thanks to improved size control at less than 100 nm. Additionally, the durability of nanotechnology-produced coatings allows for less frequent painting, resulting in cost savings and waste reduction.

2. Regulatory Compliance: The application of nanotechnology, particularly in nanomaterials, necessitates adherence to certain regulatory criteria for safety and environmental effects, as evidenced by the use of nanotechnology in pigments [11]. Manufacturers invest in R&D to meet regulatory standards and fully utilize nanotechnology's benefits to produce innovative products. Obstacles and Prospects for the Future Despite ongoing

Eco-friendly And Sustainable Pigments

The paint and coatings industry is currently focusing on the green movement and corporate social responsibility due to strict global restrictions and increased awareness of the environmental effects paints and coatings have [12]. In this sense,

Features of Environmentally Friendly Pigments

1. Biobased and Renewable Sources: We can extract environmentally beneficial dyes from naturally occurring resources like plants, minerals, or even crop leftovers. These sources have a lower carbon index than pigments made from petrochemicals, reducing reliance on newly discovered hydrocarbon resources.

2. Low-VOC Formulations: Volatile organic compounds (VOCs) are airborne substances that are known to pollute the atmosphere and harm people's health. Environmentally friendly pigments, designed with a minimal volatile organic compound (VOC) release in mind, aim to solve environmental challenges and preserve a healthy environment for both indoor and outdoor spaces [13].

3. Non-toxic and Safe: Environmentally conscious pigments prioritize biodegradable materials, thereby reducing or eliminating the addition of hazardous substances such as chromic and metal lead, among

chemical resistance, and thermal stability. The industrial, marine, and aerospace equipment sectors use these coatings to meet the performance demands of tough and varied circumstances.

4. Consumer Electronics: Coatings for consumer electronics incorporate nanopigments to enhance electrical insulation or conductivity, and to create a robust skin that resists fingerprints and scratches. These coatings enhance their appearance and effectiveness while serving as protection.

breakthroughs, significant challenges persist in volume production, cost management, and end-to-end nanomaterial management. Collaboration between academia, business, government, and the general public will promote responsible innovation in nanotechnology-based pigments, as these issues persist. In terms of the future, there is still hope for significant progress in pigment nanotechnology. More advancements in functional coatings, effective manufacturing techniques, and novel forms of nanoparticles would increase the advantages of nanotechnology across a range of industries. Another example is the paint and coatings industry, where nanotechnology will eventually contribute to improved colour quality, additional functionality, and sustainability.

developing and applying environmentally friendly colouring methods is a significant step towards producing goods and manufacturing processes that are sustainable.

others. This feature enhances end-user, manufacturer, and applicator safety in accordance with sustainable and approved solutions.

4. Biodegradability and Recyclability: To reduce the amount of green pigments disposed of in landfills and make their disposal more environmentally friendly, approximately 86% of them are biodegradable and recyclable. This feature fits in with the circular economy concept, which advocates recycling or finding new uses for things after they have outlived their usefulness.

5. Energy Efficiency in Production: When compared to their conventional counterparts, sustainable pigments typically have lower production energy costs. Because of its efficiency, a corporation uses less energy and resources, emits fewer greenhouse gases, and has a smaller overall environmental impact.

Types of Eco-friendly Pigment

1. Natural and Plant-derived Pigments: Both mineral-based and organic pigments derived from plants, fruits, and vegetables offer beautiful colour and are environmentally safe, biodegradable goods [14]. Examples are blue for indigo, which has been used in products for millennia but is currently being reintroduced more frequently; red for beetroot; and yellow for turmeric.

2. Biodegradable Synthetic Pigments: We can render synthetic pigments entirely biodegradable by incorporating organic compounds into them or creating pigment molecules that naturally decompose in their natural habitat. These pigments do a fantastic job of maintaining colour purity without harming the environment.

3. Mineral-based Pigments: Made from minerals, mineral-based pigments are safe for the environment. Examples of these pigments are titanium dioxide (white), iron oxides (red, yellow, and brown), and ultramarine blue. They are often inexpensive, tasteless, and have good heat and lightfastness characteristics.

4. Recycled Pigments: We must use newer technology to recycle and reuse pigments used in post-consumer items like old paints or recycled plastics. These pigments are environmentally benign because they reduce the demand for virgin ingredients, which in turn supports closed-loop recycling processes.

Advantages and Difficulties

1. Environmental Benefits: Eco-friendly pigments reduce emissions, toxicity, and the need for natural resources in their production. It aligns with corporate social responsibility goals as well as consumer attitudes towards sustainable products.

2. Market need and consumer perception: Growing consumer awareness of products' effects on the environment has led to a need for environmentally friendly products like paints and coatings. As a result, companies looking to target the expanding green belt of consumers may consider the bio-soluble pigment market.

3. Technical Difficulties: Compared to other pigments, there are still problems with stability, more

uniform colour tones, and production costs. We continuously investigate these issues through the discovery of novel approaches to pigment synthesis, innovative techniques for preparing pigment dispersions, and enhanced production procedures.

4. Regulatory Compliance: Businesses can only use green pigments due to the strict environmental laws of the emission sectors. Manufacturers are required to comply with established regulatory criteria concerning the production, emissions, and ecological impact of their products in various international markets.

Upcoming Developments and Trends

1. Biotechnology advancements: The use of biotechnology to produce pigments in a sustainable fashion, such as fermentation to produce natural colours that do not negatively affect the environment in the same way that synthetic processes do, offers hope.

2. Nano-enabled eco-friendly pigments: Nanotechnology may significantly enhance the performance of eco-friendly pigments by making them more robust, vivid, and long-lasting [15]. The fundamental mechanical control over the size and arrangement of pigment particles creates new opportunities for the advancement of eco-friendly coatings.

3. Collaborative projects and standards: To support the eco-friendly pigment industries, new

developments rely on industrial collaborations, research alliances, and standardization projects. In conclusion, the aforementioned activities seek to facilitate the exchange of knowledge, advance innovation, and establish industry-wide sustainability benchmarks. Sustainable pigments are an innovative step forward in the paint and coatings industry. These pigments help create a more sustainable future in accordance with global market and legal expectations because they address environmental protection, safety, and performance. As demonstrated below, innovation continues to be the primary force behind the expansion and improvement of the use of sustainable pigments, with the goal of creating a colourful yet ecologically conscious world.

Colour Matching and Replication

In the paint and coatings industry, colour matching and replication are essential since the sector must provide both an efficient production process and colour consistency for its consumers [16]. They include procedures such as colour matching from customer samples or standard references to achieve the desired level of consistency in terms of appearance

and functionality. Crucial techniques for colour matching include spectrophotometry, colour matching software, and lighting setup [17]. Spectrophotometers measure the samples' reflected light intensities in comparison to reference standards; software analyses the data to choose the best pigments. Lighting conditions also have a significant

impact on colour assessment consistency. Limitations include metamerism, substrate effects, additional applications, and environmental factors. Future trends will include automation and digitalization, as AI and machine learning can process massive datasets to anticipate acceptable pigment combinations more quickly. Along with the advent of prototype and low-

Functional Coatings and Specialty Paints

The automotive, aviation, medical, and construction industries utilise innovative, cutting-edge materials known as specialty paints and coatings to enhance the strength, energy efficiency, and utility of their equipment [18]. Among these coatings are those that offer high performance for chemicals and abrasion, anti-corrosive, anti-microbial, heat and fire resistant, self-cleaning, electroconductive, and EMI shielding [19]. They include nanotechnology, smart coatings, the next generation of resins and binders, and additives. Functional coatings have many benefits,

Digital Tools and Color Design

Another important way that digital technology has contributed is by making it easier to create, manufacture, and use colours in a variety of businesses. These tools are based on advancements in digital imaging, hardware, and software to enhance colour handling creativity and speed while maintaining accuracy. The ability to virtually examine color settings and product appearances enables designers to select the ideal color based on both customer preferences and design concepts. Spectrophotometers and colour formulation software play a crucial role in ensuring precision in colour matching and customization [20]. Colour management systems (CMS), digital imagery and

Landscape Regulatory and Compliance

Because the goal of the paint, coating, and chemical industries is to safeguard people, the environment, and the products they employ, they are especially sensitive to the regulatory framework and compliance. The GHS, ISO Standards, REACH, and EPA rules are a few of the most important laws [21]. These frameworks include clauses about chemical use, support for alternative options, and clauses about entering foreign markets. Still, dealing with many regulations is difficult and time-consuming. The company must recognise the risks, develop compliance plans, and stay up-to-date on regulatory developments in each nation. Because supply chain management entails accountability, transparency, and adherence to legal criteria, it is essential for

Consumer Trends and Colour Preferences

Consumer behaviours and colour preferences impact numerous businesses, particularly in fashion, technology, interior design, and automotive paint. Some of the factors that influence these preferences include culture and location, psychological and

volume manufacturing technologies comes the trend of product personalisation and customisation. Because of this, producers are now able to deliver precise colour matching while also keeping up with market trends and new technologies, thanks to advancements in colour science and new technologies.

including performance and durability, compliance with legal requirements, reproducibility, and originality and uniqueness. They are becoming the preferred option for green chemistry syntheses based on renewable feedstocks and low-VOC formulations since they reduce maintenance costs and duration in industrial and commercial environments. These coatings' characteristics will continue to be essential to technological progress and the capacity to handle the demands of complicated applications, both now and in the future.

photography, colour matching software, and virtual and augmented reality equipment are tools used in colour design. The automotive and aerospace industries, electronics, textile and fashion design, interior design, and architecture all employ color design. Artificial intelligence and machine learning, intelligent and interactive materials, digital formwork, and 3D printing are the upcoming trends and developments. The development of technology has improved colour design by providing a multitude of tools and platforms that let designers create, represent, and use colour in relation to a wide range of applications.

compliance. Accreditation and verification are also essential, and integrating sustainability into corporate procedures promotes policy compliance and enhances the company's reputation. The management and prevention of newly developing pollutants, the promotion of a circular economy, and the integration of digital tools and solutions in compliance are a few future trends and regulatory changes. By viewing regulatory challenges as trends towards growth and innovation, it is possible to manage them to enhance business prospects and foster a safer environment. By viewing regulations as a strategic opportunity for growth and development, businesses can embrace the challenge and contribute to the creation of a safer and more sustainable future.

emotional factors, fashion and design, ecologically friendly factors, and technology [22]. These trends include, but are not limited to, basic and monochrome designs, flamboyant and unconventional colours, ageless and adaptable designs, and personalised

designs. Electronics, fashion, interior design, and car paint use colour preferences to satisfy a variety of consumer needs and desires. Automobile manufacturers use bold accents, matte hues, and metallic finishes to set their models apart and appeal to particular consumer demographics. Furnishings and home décor also reflect the current fashion colours, becoming increasingly wearable. Fashion designers consider color preferences not only when creating clothing, but also when creating consumer gadgets. This covers the use of digital technology for

Durability and Performance Enhancements

Colour chemistry and paint technology are essential for creating superior, functional, and aesthetically pleasing coatings with a range of resistances and durability [23]. Paints and coatings have benefited from recent advancements in colour chemistry due to improvements in materials, sustainable technologies, and the durability and efficiency of these technologies. Resilience to weather, chemical and mechanical abrasion resistance, colour and fade retention, and compatibility with the substrate are a few of the important factors to take into account. Additives such as nanoparticles or nanoclays, as well as self-healing coatings that incorporate microcapsules or a polymer network to repair minor wear and tear, enhance the characteristics of paint. Low-VOC formulations and techniques, such as water-borne formulations, bio-

Techniques of Application and Efficacy

The paint business depends on better production standards, a high-quality final look, and efficient coating techniques. Additionally, they reduce faults such as substrate surface contact, thickness irregularities, and color variations that could result in a low-quality final finish. Application techniques help to improve the production line and rates by reducing material waste, time consumption, and expenses. To minimise our environmental impact, we use low-volatile organic compound (VOC) coatings, energy-efficient spray equipment, and eco-friendly processes [24]. We also use spray application systems, robotic/automated painting, powder coating and curing, and digital and smart coating systems as

The Competitive Landscape and Market Dynamics

Technology, regulations, customers, and economic factors all are impacted by the market's state and level of competition in colour chemistry and the paint industry [25]. At the moment, paints and coatings, pigments and additives, and application methods are seeing new prospects due to nanotechnology and smart coatings. Controlling VOC emissions and outlawing dangerous substances are two regulatory aspects that affect the use of paints and other coatings with low volatile organic content. Consumer preferences for durability, sustainability, and aesthetics are currently influencing consumer items,

virtual try-ons, multi-sector collaborations, and sustainable colour solutions. Businesses may prepare for customers, use colour creatively, and build relationships with target consumers by being aware of the effects of culture, design trends, and technological advancements. Therefore, being aware of these trends could aid in determining the needs of the market, developing innovative products, and maintaining competitiveness in the ever-evolving business landscape.

based resins, and recycled components, improve product performance and longevity while also reducing environmental issues. Paints and coatings with high-performance resins and binders have increased weathering resistance, chemical resistance, and durability. Markets and sectors include consumer durables and electronics, automobile OEM and refinishing, industrial and architectural coatings, and special purpose coatings. These include function surfaces and smart coatings, digital and predictive coatings, recyclable and biodegradable coatings, and more. They would lead the way in sustainability, materials science, and technology, opening up new avenues for the global development of strong, resilient, and eco-friendly coatings.

additional application techniques. These technologies are employed by the consumer products and electronics, architectural and decorative coatings, automotive and transportation, and industrial and protective coatings sectors. Some of the anticipated innovations in the paint business include nanotechnology in coatings, augmented and virtual reality in training, better surface preparation techniques, and biodegradable and sustainable paint solutions. These developments ensure long-lasting, high-quality coatings that satisfy the performance requirements for a range of applications while also encouraging innovation and competitiveness in international markets.

automobile finishes, and architectural coatings. Global economic forces, such as urbanisation and the expansion of economies in emerging areas, exert pressure on the costs of raw materials, the raw material supply chain, and pricing patterns. Due to the intense nature of the rivalry, both domestic and foreign businesses are vying for market share and profitability by differentiating their products, building their brands, finding new distribution channels, and satisfying customers. The strategic directions encompass environmental stewardship and sustainability, digitalization and industry 4.0,

emerging markets and growth prospects, risk management and organizational resilience, and collaboration across industries. In an uncertain and

intricate global market, these elements help businesses succeed more.

CONCLUSION

In conclusion, the paint industry has drastically changed the field of color chemistry due to the application of contemporary technology in color selection and coloring, as well as the introduction of new technologies like nanotechnology pigment manufacture. The aforementioned advances have improved coatings' durability and attractiveness while also aligning with the diverse, responsible green coating trends observed in other nations. Future trends predict further innovation in this field

to enhance customer expectations, boost performance, and broaden the applications of electrochemical air filters. Technological advancements, regulatory modifications, and trends regarding the color chemistry of paints and coatings continue to determine the competitive dynamics in the future. He characterises these developments as the industry's progression towards a more robust, environmentally friendly, and technologically advanced future.

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