ADVANCES IN PEARLESCENT PIGMENTS: STRUCTURE, SYNTHESIS, AND SUSTAINABILITY

A thesis submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in

CHEMISTRY

by

SONIA MAWRI
(23/MSCCHE/52)

Under the supervision of
Prof. Roli Purwar

Department of Applied Chemistry

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

June, 2025

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering Bawana Road, Delhi-110042)

CANDIDATE'S DECLARATION

I, Sonia Mawri (2K23/MSCCHE/52) hereby certify that the work which is being submitted in this major project report entitled "**Advances in Pearlescent Pigments: Structure, Synthesis, and Sustainability"** in the partial fulfilment for the award of the degree of Master of Science at Delhi Technological University is an authentic record of my own work carried out by me under the supervision of Dr. Roli Purwar (Professor, Department of Applied chemistry, DTU)

I further declare that the project report has not been submitted previously to any other institute/university for the award of any degree or diploma associateship, fellowship or other recognition or any other purpose whatsoever. Also, it has not been directly copied from any source without giving its proper reference or citation.

Sonia Mawri
(2K23/MSCCHE/52)
Place: Delhi
Candidate's Signature

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering Bawana Road, Delhi-110042)

CERTIFICATE BY THE SUPERVISOR

Certified that Sonia Mawri (2K23/MSCCHE/52) has carried out their search work presented in this thesis entitled "**Advances in Pearlescent Pigments: Structure, Synthesis, and Sustainability"** for the award of Master of Science from the Department of Applied Chemistry, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student herself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

Signature
Prof. Roli Purwar
Supervisor
Delhi Technological University

Date: 20-06-2025

ACKNOWLEDGEMENT

To start with, I would like to pay our heartiest thanks of gratitude to our institutional guide **Prof. Roli Purwar** (Professor, Department of Applied Chemistry, Delhi Technological University) for her continuous motivation, healthy scrutiny and her coordination without which this feat would not have been possible.

I am also grateful to **Prof. (Dr.) Anil Kumar**, Head of the Department, Department of Applied Chemistry, Delhi Technological University, for providing us the constant support to the best heights for this project work.

I would also like to thank the faculty members **Dr. Ram Singh, Dr. Archna Rani, Dr. S.G. Warkar, Dr. Richa Srivastava, Dr. Deenan Santhiya, Dr. Raminder Kaur, Dr. Saurabh Mehta, Dr. Poonam Singh, Dr. Devender Kumar**, for their support and encouragement throughout the course of this project.

Special thanks to PhD scholar, **Ms. Megha Bhoj** for her kind contribution and patience throughout the project.

Last but not least, I want to sincerely thank our family and friends for supporting us during our hard workdays and for providing the inspiration that kept us going.

Sonia Mawri

Advances in Pearlescent Pigments: Structure, Synthesis, and Sustainability

ABSTRACT

Pearlescent pigments are indispensable materials in numerous industries, prized for their ability to generate captivating luster and vibrant optical effects. These pigments typically consist of thin metal oxide layers—such as titanium dioxide, iron oxide, aluminum oxide, and zinc oxide—deposited on transparent mica platelets. Their unique optical performance arises from the interference of light waves within these multilayer structures, producing dynamic color variations that shift with changes in illumination and observation angles. The structural characteristics and synthesis methods utilized to create these pigments are thoroughly examined in this paper, emphasizing the significance of exact control over substrate shape, layer thickness, and crystalline phase composition.

To clarify the connection between pigment structure and optical characteristics, advanced characterisation techniques like as UV-visible spectroscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD) are covered. Applications of pearlescent pigments extend to cosmetics, automotive coatings, packaging, plastics, and even food and textiles, where their ability to produce luxurious finishes and functional performance—such as UV protection and heat management—has driven widespread adoption.

The review also explores contemporary challenges associated with environmental and regulatory concerns, emphasizing the shift towards greener production techniques and the development of hybrid or sustainable alternatives. These efforts aim to reduce the environmental footprint while maintaining or even enhancing the optical performance of pearlescent pigments. Overall, this paper offers a comprehensive perspective on the science and technology of pearlescent pigments, highlighting their versatility and the ongoing commitment to environmentally responsible innovation within this dynamic field.

Keywords- Pearlescent effect, metal oxide, mica titania, interference

CONTENTS

3. CHAPTER 3 CONCLUSION AND REFERENCES

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

1. Introduction

1.1 Inorganic pigments

The use of special effect inorganic pigments is continuously on the rise, especially in industries like automotive manufacturing and cosmetics. In contrast to dyes, which dissolve in conventional solvents and binders, pigments are insoluble materials that alter the color of a substrate by staying on its surface rather than being absorbed. Although pigments can be either organic or inorganic, inorganic pigments have become the preferred choice for industrial applications due to their stability and versatility.[1]

Depending on the angle from which they are seen or lighted, the apparent color of these special effect pigments changes according to the principle of light interference. [2] The thin, optically active layers of these pigments are what create this striking visual phenomenon, allowing coated objects to shift in color and brilliance depending on the viewer's perspective.

Pigments are generally defined as colored solids that are both chemically and physically stable within the medium they are dispersed in, remaining unaffected by the surrounding environment. [3], [4] This inherent stability ensures that, when these pigments are applied as coatings, they remain fixed to the substrate without dissolving or breaking down.[5] Consequently, special effect inorganic pigments not only enhance the visual impact of products but also provide long-lasting durability and resistance to environmental factors, making them especially valuable for high-end finishes in both automotive coatings and cosmetic formulations.

Although there are two types of pigments—organic and inorganic—the most often employed kind consists of insoluble granules that are uniformly dispersed throughout the coating's matrix.[6] Recent research in the industrial pigment sector has primarily focused on three core objectives: improving the performance features of inorganic pigments, replacing harmful and environmentally unfriendly chemicals to meet stringent new national and international standards, and enhancing the economic viability of already available pigments.[7]

Special effect pigments not only produce striking angular and spatial variations that contribute to a sparkling or glitter-like appearance but also create mesmerizing iridescent effects that shift colors with changes in the light source. These phenomena are largely attributed to thin-film interference, which modifies how the light interacts with the pigment particles and coatings.[8]

In the broader classification system, pigments are typically divided into four categories: white pigments, colored pigments, black pigments, and effect pigments. For instance, white pigments scatter incident light uniformly in all directions, leading to diffuse reflection and a bright, opaque appearance. Effect pigments, which include both pearl luster and metal effect pigments, are distinguished by their unique light-scattering properties and the ability to create visually dynamic surfaces.[9]

1.2 Special effect pigments

Effect pigments are typically divided into **two major categories** based on their structure and how they interact with light to create visual effects: **layered pigments** and **substrate-free pigments**. Layered pigments, often brittle and constrained by their specific chemical composition, are generally less flexible in application. Substrate-free pigments, on the other hand, are manufactured by coating thin, plate-like substrates—such as mica or alumina—with layers of materials that possess high refractive indices, like titanium dioxide, iron oxide, or their mixtures. This careful layering process imparts these pigments with unique optical properties that significantly enhance their visual impact.[10]

Although the term “effect pigment” is sometimes used interchangeably with “high-performance pigment,” it is important to understand that high-performance pigments actually encompass a broader range of both organic and inorganic pigments that are valued for their enhanced material durability and performance traits, rather than solely for their optical effects. [11] In the context of special effect pigments, the optical effects arise from the interaction of light waves reflected at various interfaces within the metal oxide layers. The thickness of these coatings determines the intensity and nature of the interference effects, resulting in vibrant, multi-dimensional color shifts and finishes. [12]

Special effect pigments offer various optical benefits, including pronounced color changes, a sense of depth and dimension, and even the ability to mimic the natural luster of real pearls. [13] Due to these distinctive visual features, special effect pigments are employed in a wide range of industries—from automotive coatings, plastics, and paints to cosmetics and electronics. The vibrant, lustrous hues achieved through the controlled layering of light-absorbing metal oxide films make these pigments highly sought after for aesthetic and functional enhancements. [14] Among these, the two most prominent categories are metallic effect pigments, which impart a mirror-like sheen, and pearlescent effect pigments, known for their soft, iridescent glow. **Figure 1** illustrates how different pigment structures influence light reflection, scattering, and interference:

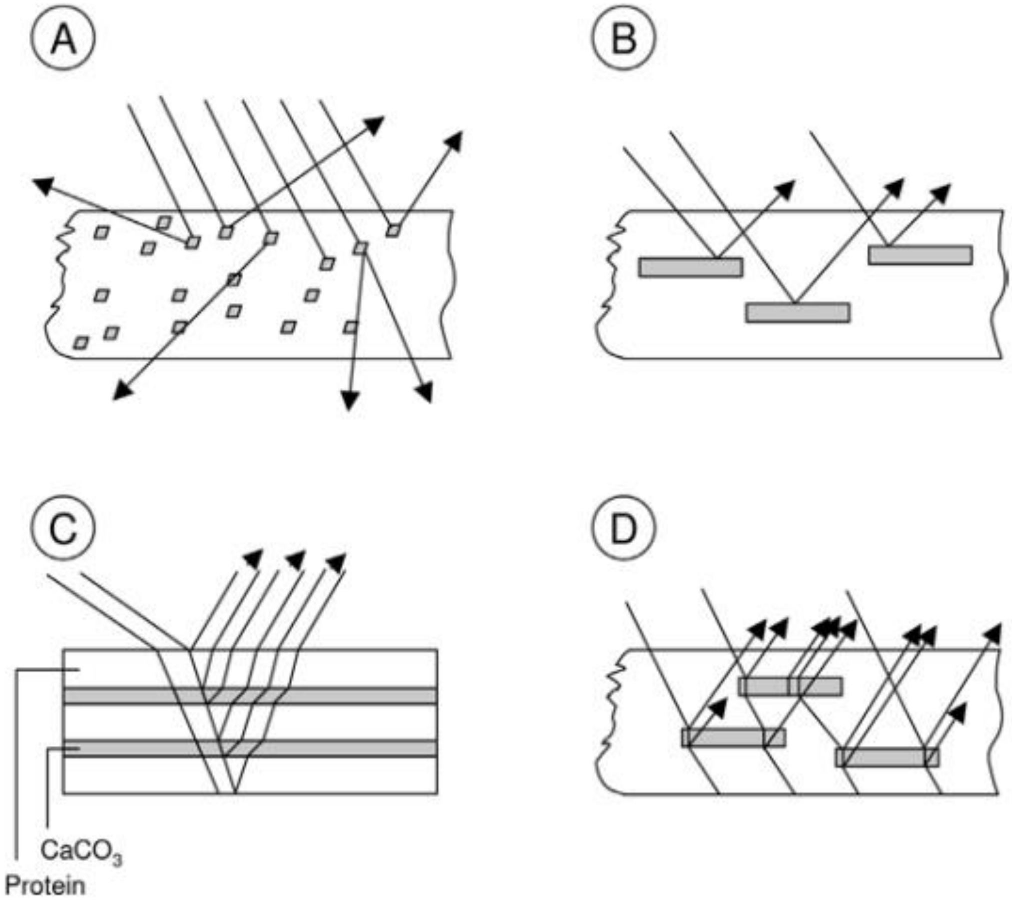

Figure 1: A) conventional pigment; B) metal effect pigment; C) natural pearl; D) pearl luster pigment [15]

1.2.1 Metallic effect pigments-

Pigments that provide a metallic-like appearance to the surfaces they coat are a key focus in the field of special effect pigments. One prominent group within these pigments are those that are substrate-free, meaning they consist of a uniform, single material rather than layered composites. [16] Angle-dependent optical phenomena are achieved through the use of either multilayer film structures or transparent single-layer coatings—such as varnishes, plastics, or rubber—in combination with plate-like effect pigments that display various optical characteristics. These pigments find utility in both functional applications like corrosion protection and decorative uses in industries including automotive and cosmetics. [17]

The most classic example of metallic coatings involves aluminum-flake pigments dispersed in clear solutions. These aluminum flakes are typically thin, flat, and round, with diameters that range from 5 to 50 micrometers. When applied, they generally align parallel to the surface, which enhances the reflection of light in the specular direction and creates a brilliant metallic sheen. [18] Common metallic effect pigments include bronze powder, aluminum flakes, and zinc flake powder. Historically, these materials were produced through traditional processes such as the stamping process, the hametag method, and dry milling.[19]

Stamping machines are commonly employed to process metal granules and convert them into metal effect pigments. The production of metal flakes typically involves ball milling techniques, including both wet milling and the dry milling Hametag method. During this process, lubricants are added to achieve either leafing or non-leafing properties and to prevent cold welding of the metal flakes. [20]

Metal flakes stand out due to their distinctive coloration, which contrasts with the typically vivid base coat visible through the transparent resin or matrix they're embedded in. This color difference complicates the process of comparing metallic materials with one another. [21] Unlike traditional opaque coatings, metallic coatings are highly sensitive to the geometry of the light source and the viewing angle. This sensitivity creates a dynamic visual effect that accentuates the object's curves and contours, thereby enhancing its overall aesthetic appeal. [22] Since the 1930s, metallic coatings have seen widespread adoption, with approximately 80% of all modern vehicles now featuring these visually striking finishes. [23]

Beyond automotive applications, these pigments can be incorporated into polymers to create fresh metallic color effects or can replicate the appearance of real metals when combined with transparent organic pigments. Bronze pigments, for instance, are used to achieve warm, copper or gold-like appearances through similar methods. [24] The underlying mechanism of these effects lies in the phenomenon of light interference. Under low light conditions, these pigments produce color variations, while under intense, direct lighting, they exhibit vibrant rainbow hues. Such metallic pigments are utilized in a diverse array of products including packaging, paints, coatings, plastics, and textiles, and are typically manufactured using state-of-the-art thin-film deposition technologies. [25]

Functionally, metallic pigments behave like numerous tiny mirrors. The metallic appearance they produce is highly dependent on how the pigment particles are oriented in relation to the light source and the position of the observer- an effect only achievable with lamella-shaped, light-reflective particles. Production process flowcharts for both dry milling and wet milling methods outline these steps in greater detail, which are given in **Figure 2** and **Figure 3.** [26]

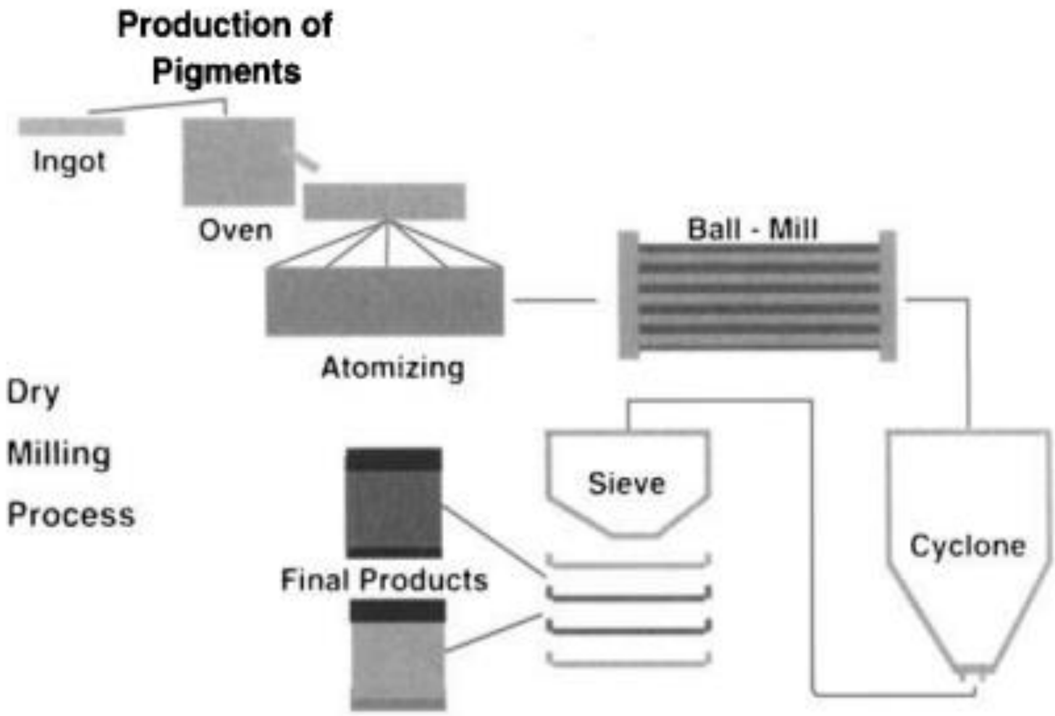

Figure 2: Manufacturing of metal pigments using the dry milling method.

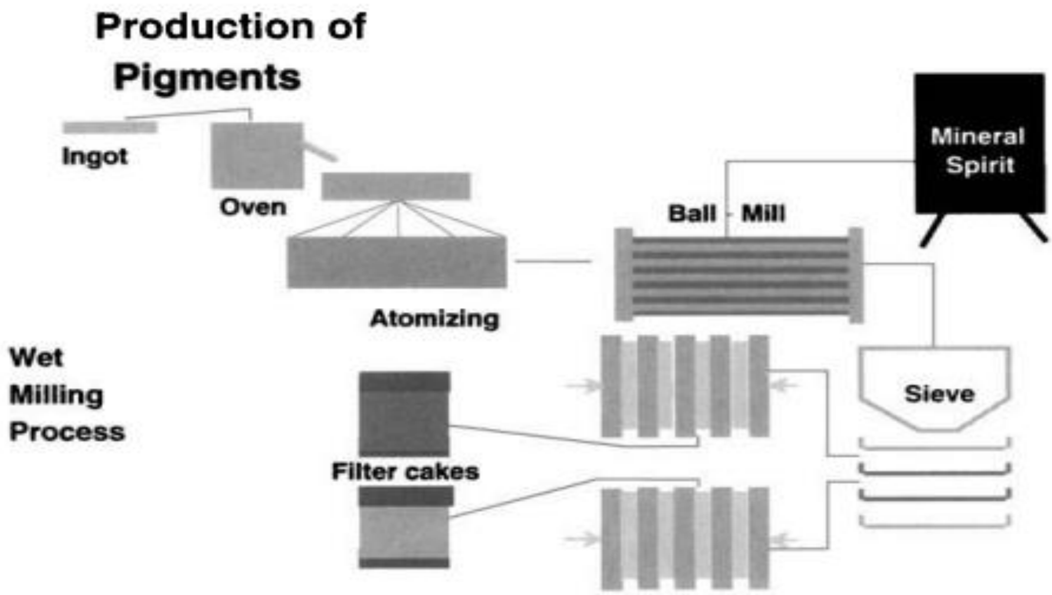

Figure 3: Manufacturing of metal pigments using the wet milling method.

1.2.2 Pearlescent effect pigment-

Pearlescent pigments are produced by applying layers of metal oxides, like titanium dioxide or iron oxide, onto thin, flat substrate particles. When light hits these coated particles, it reflects from both the top and bottom surfaces of the oxide layers, resulting in interference that creates distinct optical effects. The specific interference colors depend on the thickness of the applied coatings. [12] A pearlescent pigment is defined as one that exhibits a shiny, pearl-like effect due to optical phenomena that vary with viewing angle. This effect arises from alternating transparent layers with differing refractive indices, which cause light interference. [27] These pigments are usually made of transparent mica platelets covered in extremely thin layers of metal oxide. Their brightness, color intensity (chroma), and color shift depend significantly on both the lighting and the viewing angles. [28]

One key advantage of pearlescent pigments is their exceptional light resistance, making them especially suitable for printed materials or products designed to endure outdoor exposure or strong lighting conditions. [20], [28], [29] However, this durability is often dependent on the specific application. For instance, pearlescent pigments can enhance the light-fastness of printed materials in flexographic printing when mixed with absorption pigments. [30] Conversely, they have been shown to decrease light stability when used to overprint ink-jet prints. [31]

The distinctive goniochromatic properties of pearlescent pigments are the result of constructive interference caused by the differences in refractive indices across the layered structures. In practical applications, the interference color—A common method for identifying and distinguishing pearlescent pigments is to utilize the dominant wavelength of light reflected at a specific specular angle. [32]

The design of multilayer pearlescent coatings was inspired by the natural structure of pearls, which are composed of alternating transparent layers with varying refractive indices. In contemporary pigment formulations, minerals such as silicon dioxide, iron (III) oxide, chromium (III) oxide, and titanium dioxide are sequentially layered over a base substrate, typically natural or synthetic mica (muscovite). The commercialization of pearlescent pigments began in the 1970s and saw significant growth in the 1990s with the advancement of methods for depositing multiple distinct material layers onto mica flakes. [33]

Nowadays, most color-enhancing pearlescent pigments are made by applying colored metal oxides with high refractive indices on mica surfaces. For example, applying a thin layer of Fe_2O_3 to mica imparts a bronze color, and adjusting the layer's thickness allows precise control over the resulting hue. [34] In addition to creating vibrant, color-shifting fabrics, pearlescent effect pigments are highly valued for their ability to generate striking, angle-dependent color effects, enabling innovative design possibilities across various applications. [35] Rather than relying on absorption of light, pearlescent pigments achieve their shimmering appearance through the phenomenon of light interference. Their unique optical effects, combined with excellent chemical stability and ease of use, make these pigments especially attractive in many industrial and design contexts. [36]

For coatings applications, pearlescent pigments are typically available in three particle size ranges: a micro fraction (< 15 µm) that provides a satin finish with high coverage; a normal fraction (10–40 µm) for a pearl luster with lower hiding power; and a medium fraction (5–25 µm) for smooth, silky finishes with intermediate coverage. [37]

In a notable study by Václav Štengl et al. (2003), a method was described to produce intensely colored lamellar mica particles. This method produces vivid pearlescent colors with regulated characteristics by uniformly hydrolyzing metal sulfates in aqueous solutions when mica particles are present. [38]

Pearlescent colors based on iron oxide and titanium dioxide are among the most widely used. Each metal oxide contributes to different functional and optical properties, allowing for a wide range of applications and effects.

1.3 Different metal oxide pearlescent pigments

1.3.1 Titanium Dioxide Pigment

Titanium dioxide (TiO_2) is among the most commonly employed minerals in the chemical sector, with its commercial use beginning in the early 20th century. Due to its adaptable properties, it plays a crucial role in numerous applications such as paints, plastics, paper, sunscreens, cosmetics, and food products. [39], [40], [41] Beyond conventional TiO_2 pigments, there are advanced variants that include metal platelets coated with oxides, mica platelets with oxide layers, oxide-coated silica and aluminum flakes, platelet-shaped single crystals, and liquid crystal polymer-based platelets. [42]

On an industrial scale, titanium dioxide pigments are predominantly manufactured using two principal methods: the sulfate process and the chloride process. These processes typically utilize TiO_2 slag as the starting raw material, which is a by-product that contains a high concentration of titanium dioxide along with pig iron. [43]

For the creation of TiO_2/mica pigments, the process generally involves depositing TiO_2 layers onto mica substrates within an aqueous suspension. This is followed by a calcination step, during which crystalline TiO_2 is formed. The final optical properties and pearlescent effects of TiO_2/mica pigments depend heavily on the ratio of anatase to rutile (A-R) phases in the TiO_2 layer, as well as the phase transition behavior that occurs during calcination. [44]

Titanium dioxide platelets that exhibit interference colors yet are not layered onto any substrate are termed unsupported mica-titania, or platy TiO_2 pigments. [45] These substances are electrically insulating, non-flammable, self-extinguishing, and pose no risk to human health, which makes them ideal for numerous applications. As a result, mica-based pearlescent pigments are widely utilized in thermoplastics, paints, cosmetic products, food packaging, children's toys, and automotive coatings. [46]

Due to their unique optical properties—such as the appearance of depth and striking visual effects—mica-titania pigments hold significant appeal for ceramic decoration. Traditional ceramic pigments often cannot replicate these effects. Recently, research has explored the possibility of substituting expensive metals with mica-titania pigments in low-fired ceramic artwork to achieve similar luster effects. [27]

Platy TiO_2 pigments, also called unsupported mica-titania, are a specialized form of titanium dioxide platelets that produce interference colors without requiring a substrate. [47] These colors are mostly produced using the two widely recognized commercial processes of sulfate and chloride. Both processes rely on raw materials such premium TiO2 slag and synthetic rutile derived from ilmenite ore. Smelting iron oxides into liquid iron in massive electric arc furnaces is a popular method for producing titania slag as the precursor material. [48]

It's worth noting that one method for stabilizing the rutile phase of TiO_2 during calcination involves using a thin layer of tin oxide as an intermediate between mica and the titanium dioxide coating. However, the use of tin oxide in pearlescent pigments is restricted in certain applications. For example, tin oxide-based pearlescent pigments cannot be used in polymer products intended for food contact or in cosmetics due to safety concerns and regulatory limitations in various countries. [45]

Figure 4 shows the synthesis of TiO_2-coated mica pigments. Muscovite mica is ground into flakes, coated with TiO_2 via hydrolysis of $TiOCl_2$ in NaOH, then filtered, dried, and calcined to form pearlescent pigments.

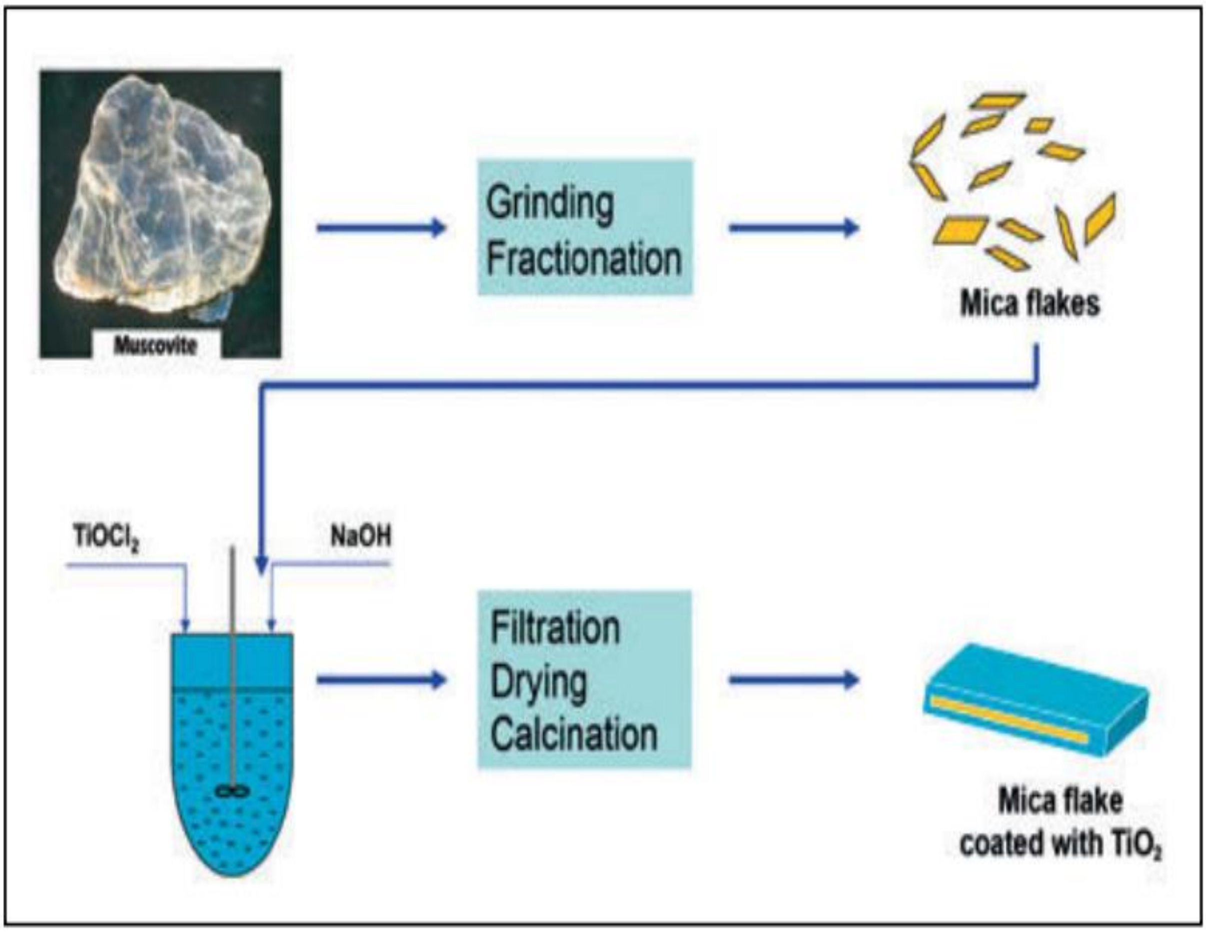

Fig 4: Process scheme for metal oxide mica pigments. [49]

As detailed by Berna Burcu Topuz et al. (2011), the production of TiO_2-coated mica pigments begins with the meticulous preparation of the mica substrate. This involves sieving the mica to achieve the desired particle size, followed by heating and acid treatment to eliminate impurities and fine particles. In the next step, titanium tetrachloride ($TiCl_4$) is carefully hydrolyzed in cold hydrochloric acid to produce titanium oxychloride ($TiOCl_2$). This intermediate compound is then deposited onto the mica in an acidic slurry under controlled pH and temperature conditions.

Following deposition, the coated mica undergoes aging, washing, drying, and calcination processes to yield an anatase-phase TiO_2 coating. To convert this to the more stable rutile phase, a tin source ($SnCl_4$) is introduced to dope the coating with tin oxide (SnO_2) before repeating the TiO_2 deposition step. This well-controlled synthesis method allows precise adjustment of the pigment's composition and crystalline phase, ultimately tailoring its optical effects and ensuring high-quality, consistent pearlescent pigment production. [50]

Figure 5 shows how light reflects and interferes within a TiO_2-coated mica layer, producing angle-dependent color based on optical path differences and refractive indices.

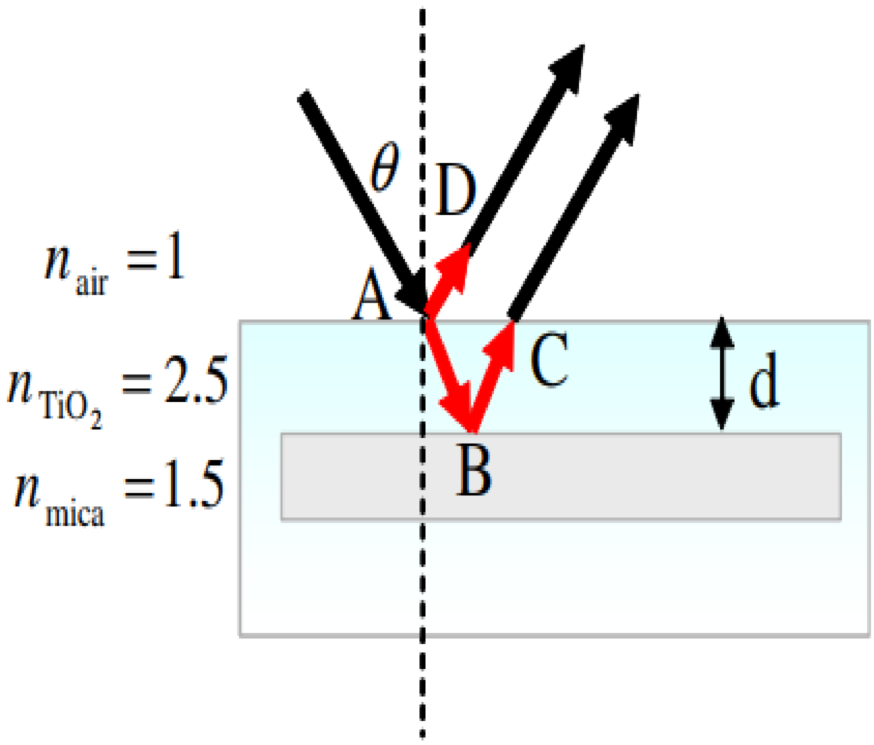

Fig 5. Light interference in a mica substrate covered with titanium dioxide.[12]

1.3.2 Iron oxide-coated mica pigments

Mica pigments coated with iron oxide are known for their excellent thermal stability. They are also non-conductive, do not ignite or self-ignite, and are considered safe for human health. [20] These properties make mica-based pearlescent pigments perfect for application in a wide range of goods, including paints, food packaging, cosmetics, thermoplastics, children's toys, and car coatings. Since their angle-dependent optical effects are hard to reproduce by photography or photocopying, they are also ideal for security purposes; in fact, a number of countries have actively promoted their use on banknotes to discourage counterfeiting. [51]

Iron oxide–high lustre earth tone mica pigments are created by combining mica platelets with iron oxide coatings. This results in rich, metallic colors—particularly striking reds and copper tones—with improved hiding power. Because of their intense color and shiny finish, these pigments are widely used in automotive, cosmetic, and decorative coatings to provide a luxurious, attention-grabbing appearance. [37]

Mica itself is a sheet silicate (alumosilicate) mineral, and in these pigments, tiny, thin platelets of mica serve as the substrate for ultra-thin coatings of metal oxides like iron (III) oxide and titanium dioxide. As light interacts with these thin layers, it reflects at their surfaces and phase boundaries, producing vibrant interference colors similar to those seen in soap films. [52]

Red iron oxide, also known as hematite (α-Fe_2O_3), is one of the earliest pigments known to humankind. [53] These reddish-orange hematite pigments have been in use for centuries and can be encapsulated for ceramic applications. Historically, hematite has been recognized as a safe, naturally occurring red pigment used in pottery since prehistoric times. Its abundance and low cost make it an excellent choice for coating mica substrates to achieve bronze luster effects in decorative applications. [54]

Hematite's hue varies according on the circumstances, though. When pigments are incorporated into glazes, ceramic bodies, or porcelain enamels for use in ceramic applications, they must be chemically inert and insoluble in molten glass. This requires that these coloring powders maintain both chemical and thermal stability at elevated temperatures. [55] To ensure a vivid and stable red color in ceramics, hematite needs to be encapsulated within a more thermally stable phase such as silica or zircon. Encapsulation within zircon-based composites, for example, provides protection against high temperatures and harsh chemical environments. [56].

To address these challenges, the current study utilized the sol-gel technique to synthesize Fe_2O_3–$ZrSiO_4$ composite pigments. This approach enables the production of finer, more uniform pigments at lower temperatures without relying on mineralizers. The resulting Fe_2O_3–$ZrSiO_4$ pigment is tailored for high-temperature firing applications in ceramic manufacturing. [57]

Table 1: Synthesis table based on the mica/Fe_3O_4 pearlescent pigment preparation described by Liang Xiaojuan et al., [58]

S.No.	Synthesis Parameter	Condition/Value	Description/Role
1.	pH	≥ 9.2	Alkaline environment essential for co-precipitation of Fe_3O_4 on mica surface.
2.	Sodium hydroxide (NaOH) concentration	0.5 mol/L	Controls the alkalinity and facilitates precipitation of Fe^{2+} and Fe^{3+} ions to form Fe_3O_4 nanoparticles.
3.	Fe^{3+} to Fe^{2+} molar ratio	1.6 : 1	Proper ratio critical for forming magnetite (Fe_3O_4) phase instead of other iron oxides or hydroxides.
4.	Stirring speed	138–151 rpm	Ensures uniform dispersion and deposition of Fe_3O_4 on mica flakes for smooth, compact coating.

5.	Reaction temperature	70–80 °C	Maintains reaction kinetics suitable for controlled growth of Fe_3O_4 nanoparticles on mica.
6.	Calcination temperature	350 °C	Heat treatment to improve crystallinity and adhesion of Fe_3O_4 coating on mica substrate.
7.	Calcination duration	3 hours	Sufficient time to stabilize the coating and enhance pigment properties such as color depth and durability.

Figure 6 below shows the synthesis of **mica-based pearlescent pigments** doped with metal salts. Mica and soluble salts are mixed and stirred, followed by **NaOH-induced precipitation**, filtration, drying at 100 °C, and **calcination at 650 °C**. The resulting products—Ce-Fe/M and Zr-Fe/M—exhibit distinct colors and surface textures compared to raw mica.

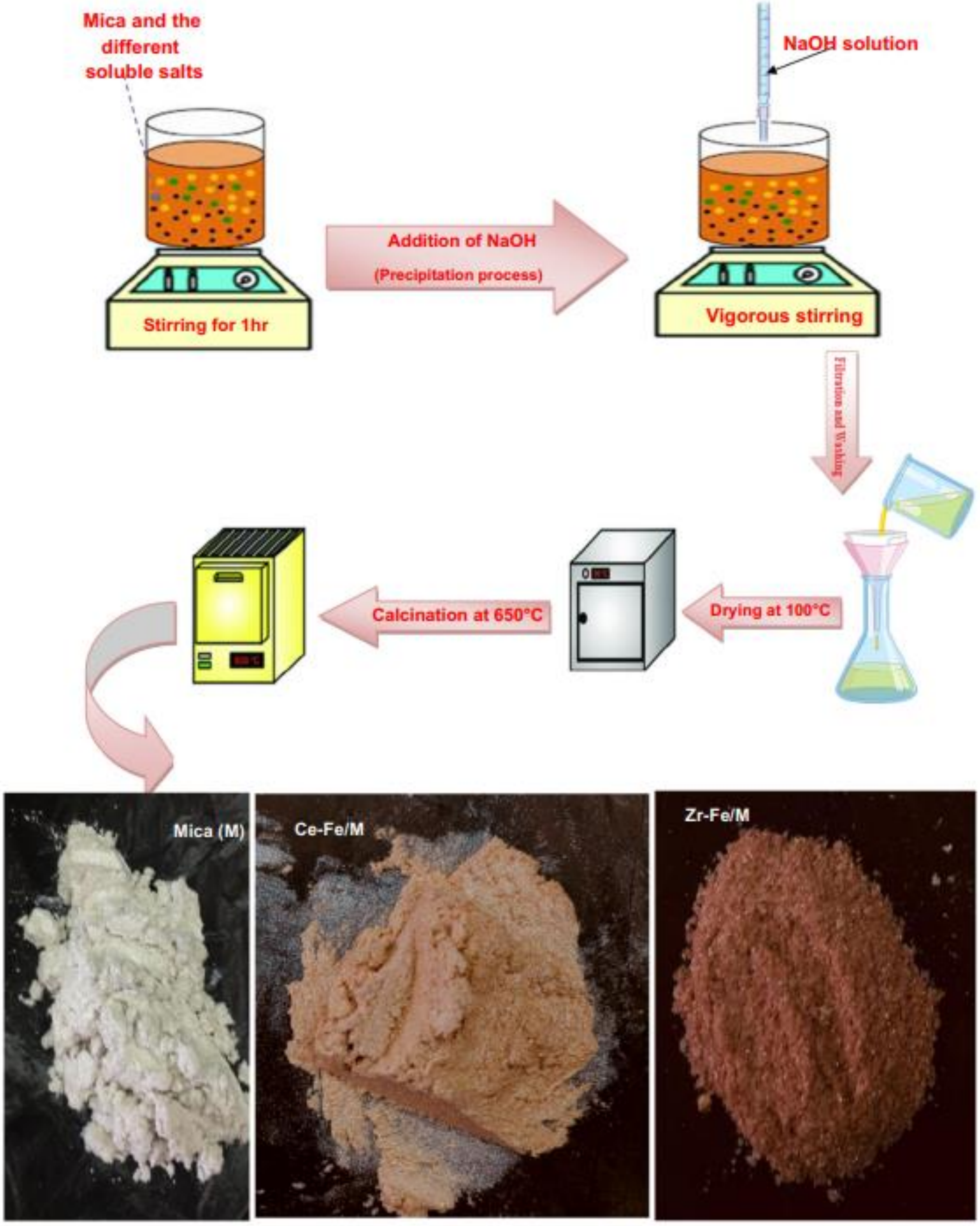

Figure 6: Preparation process of oxide coated mica pigments. [59]

1.3.3 Aluminium flake pigments

Aluminum pigments, composed of extremely thin, flat flakes, have long been used as metal-based pigments due to their striking metallic sheen and excellent covering ability. [60] These characteristics make them perfect substrates for pigments with angle-dependent optical effects, and attempts have been undertaken to create these pigments utilizing electrochemical reaction techniques that start with aluminum flakes. [61]

The typical industrial method for achieving a metallic-effect finish involves combining a metallic pigment with a transparent, colored pigment. Aluminum flakes, known for their excellent heat and UV resistance, serve as the metallic pigment, while the transparent colored component is typically an iron oxide pigment. [62]

To overcome the inherent reactivity of aluminum pigments with water, a protective silica coating is first applied. These silica-coated aluminum pigments (Al/SiO_2) are then used as substrates for producing blue aluminum pigments by depositing a layer of Prussian Blue ($Fe_4[Fe(CN)_6]_3$). The interaction of light with the Prussian Blue layer creates a unique absorption and reflection effect, earning these materials the name "blue pearlescent pigments." Careful optimization of the coating processes and reaction conditions is critical to achieving maximum optical performance from these blue aluminum pigments. [63]

When compared to traditional pearlescent pigments, aluminum pigments designed for plastic applications tend to have larger particle sizes and superior shear resistance. Aluminum pigments reflect light directly, while pearlescent pigments manipulate and distort light to create their visual effects. As a result, pearlescent pigments have a lighter flop effect and lower hiding power, while aluminum pigments exhibit a much stronger hiding capability and a darker flop effect, making them especially effective for creating intense, metallic-looking finishes. [64]

The chemical vapor deposition (CVD) method for producing aluminum flake-based pigments involves the following sequence of steps:

1. At around 450 °C, aluminum flakes are first fluidized in a nitrogen gas atmosphere.
2. Next, oxygen and iron pentacarbonyl ($Fe(CO)_5$) are added to the fluidized bed.

3. These reactants are extensively diluted in nitrogen gas to ensure that the resulting iron oxide coating is applied uniformly to the aluminum flakes.
4. Once in the reactor, the $Fe(CO)_5$ decomposes and reacts with oxygen to form iron oxide.
5. This newly formed iron oxide subsequently coats the aluminum flakes evenly.
6. By altering the reaction time throughout the deposition process, the iron oxide layer's thickness may be accurately regulated.

This technique produces pigments that create visually appealing color effects, including hues of reddish metal, orange, and gold. For further enhancement and customization of aluminum-based pigments, an additional silica layer can be deposited onto these coated flakes via wet-chemical methods. [65] Synthesis scheme for aluminium flake pigments **Figure 7**:

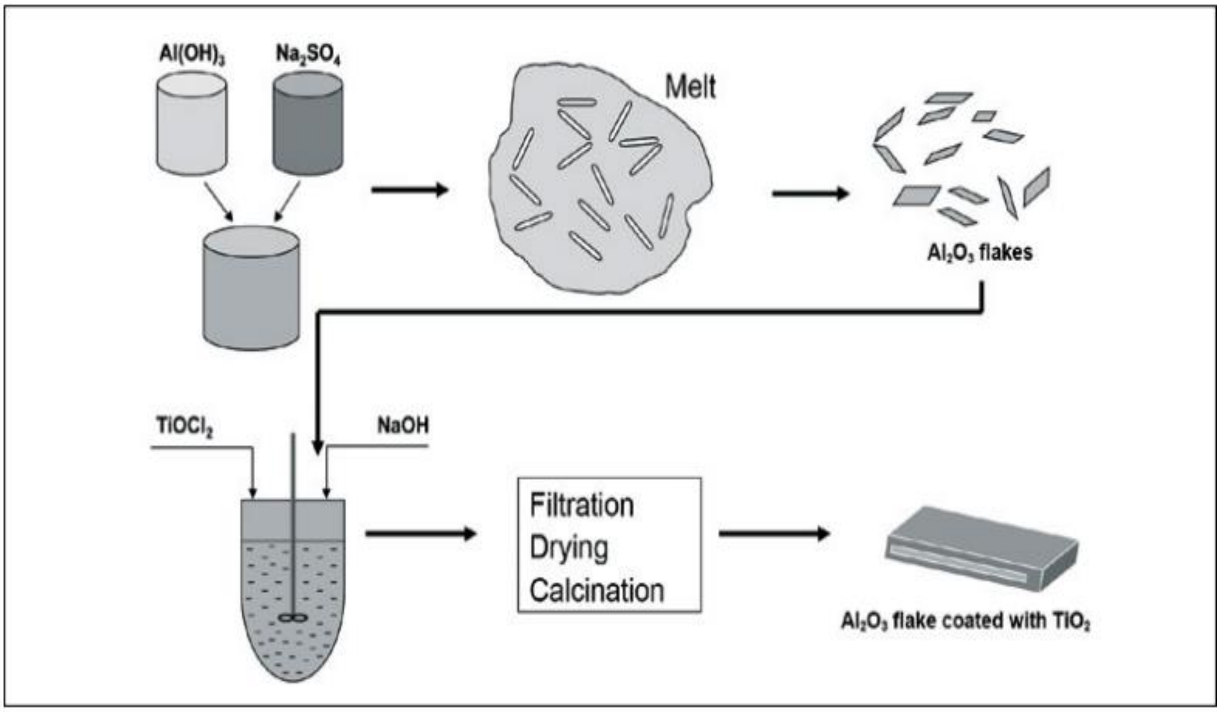

Figure 7: Synthesis scheme for Al2O3 flake pigments. [49]

CHAPTER 2

2.1 Literature Survey

2.1.1 Difference between Pearlescent effect pigment and metallic effect pigments

In coating applications, metal effect pigments are highly prized, especially for their remarkable ability to conceal. To produce coatings that provide an enticing blend of depth, color intensity, and overall coverage, these pigments are frequently used with transparent pearlescent pigments in vehicle finishes. This combination leads to visually dynamic and rich surface effects that enhance the aesthetic appeal of vehicles. [66]

Although pearlescent pigments differ from metal flake pigments in that they create thin-film interference effects, there are notable similarities. For example, metal and iridescent pigments can be blended to achieve unique finishes, and certain metal flakes can be engineered to mimic the appearance of pearlescent pigments. [67]

Measuring the color of effect coatings—such as those containing metallic or pearlescent pigments—requires special attention to the geometry of both lighting and detection. This is because the apparent color can vary significantly depending on the angles at which it is illuminated and observed. By calculating a weighted average of the measured color differences at three distinct geometric angles, the perceived overall color difference between samples can be captured fairly accurately for many metallic effect materials.[68]

Key differences between pearlescent and metallic pigments include:

- **Pearlescent pigments**: These exhibit more significant changes in color and reflectance with changing viewing angles (optical anisotropy). As a result, variations in brightness (lightness) and vividness (chroma) are more noticeable.

- **Metallic pigments**: While also showing anisotropic effects, these are generally subtler and less intense compared to those seen in pearlescent pigments.[69]

2.1.2 Comparison of properties of different pigments

Property	Pearlescent Pigments	Metallic Flake Pigments	Iron Oxide-Coated Micas
Transparency	Transparent/Semi-transparent	Opaque	Semi-transparent/Opaque
Light Reflection	Layered, sense of depth	Mirror-like, flat	Interference and absorption
Interaction with Colorants	Enhances, brightens colors	Subdues, muddies colors	Enhances and adds some opacity
Opacity/Coverage	Low, poor coverage	High, excellent coverage	Moderate coverage
Electrical Conductivity	Non-conductive	Conductive	Non-conductive
Suitability for Electrostatic Spraying	Suitable	Not suitable	Suitable
Surface Smoothness Impact	Critical for luster	Critical for brightness	Important for color/coverage

Table 2: A detailed comparison between **pearlescent pigments**, **metallic flake pigments**, and **iron oxide coated mica pigments** focusing on their optical properties, interaction with colorants, coverage, and electrical behavior. [70]

2.1.3 Existing Literature

In 2007, A. Mirhabibi and colleagues explored a novel approach to synthesizing gold pearlescent pigments by heat-treating natural mica (phlogopite) instead of relying on expensive metal oxide coatings. They used differential thermal analysis to pinpoint the optimal heat-treatment temperatures for the mica. After heat treatment, the mica was milled and sieved to achieve specific particle sizes suitable for pigment use. Analysis using X-ray diffraction (XRD) showed that the mica had transformed into phases such as forsterite and leucite. Goniospectrophotometry confirmed that the resulting pigment exhibited a vibrant yellow-gold reflectance, demonstrating that this straightforward, cost-effective method can produce attractive decorative pigments. [71]

In the same year, Kim T et al. (2007) investigated how pH influences the transformation of titanium dioxide (TiO_2) from the anatase to the rutile phase during pigment synthesis. Their findings showed that lower pH values reduce both the crystallinity and size of the crystals, which in turn lowers the temperature required for the phase transition. Since the rutile phase enhances the luster of the final pigment, this transformation is a key factor in pigment quality. XRD was employed to analyze the phase changes, confirming the pivotal role of pH control in optimizing pigment characteristics. [72]

In 2012, Qiang Gao and colleagues introduced an innovative low-temperature method to synthesize rutile TiO_2-coated mica pigments. Their technique involved first depositing manganese dioxide (MnO_2) on the mica substrate before applying the titanium dioxide layer at a mild temperature of 70 °C, eliminating the need for traditional high-temperature calcination.

The presence of MnO_2 facilitated the formation of rutile TiO_2 with distinctive needle-like and nanoflower morphologies. The resulting pigments exhibited excellent photostability and pronounced pearlescent effects, making them particularly well-suited for durable coatings and decorative finishes. [73]

Chen Jing and colleagues synthesized cobalt aluminate ($CoAl_2O_4$) nanoparticles using a microemulsion technique, which were then coated onto mica-titania substrates to produce striking blue pearlescent pigments. The resulting $CoAl_2O_4$ nanoparticles had an average size of around 20 nm and displayed uniform dispersion across the mica-titania surface. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analysis verified that the nanoparticles exhibited a spherical shape and possessed a spinel-type crystal structure. The researchers established optimal synthesis parameters: a 1:1 molar ratio of cobalt oxide (CoO) to aluminum oxide (Al_2O_3) and a $CoAl_2O_4$ coating ratio of 3.7–4.6% by weight. Their findings highlight the microemulsion approach as an effective means to produce high-quality cobalt blue pearlescent pigments with vivid color and uniform coatings. [74]

Using homogenous precipitation processes, M. Cheraghipoor et al. concentrated on producing green pearlescent pigments in 2020 by applying thin layers of nickel oxide on mica (biotite) and mica-titania platelets. They evaluated three different synthesis approaches and found that Method 1—employing sodium hydroxide at room temperature—was the most efficient and economically feasible. The effective deposition of the nickel oxide films while maintaining the integrity of the mica structure was verified by analytical methods such as differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), X-ray diffraction (XRD), and X-ray fluorescence (XRF). [75]

The synthesis of green mica-nano Cr_2O_3 pearlescent pigments involves the careful deposition of chromium precursors onto mica flakes, followed by calcination at various temperatures. By adjusting both the chromium content and the heat treatment temperature, Cr2O3 nanoparticle size and production on the mica surface are controllable by researchers. These synthesis parameters are essential in establishing the optical characteristics of the final pigment, including its pearlescent luster and color intensity. [76]

Wu N and colleagues systematically explored how specific reaction parameters impact the formation of SiO_2 coatings on α-Al_2O_3 pigments using the Liquid Phase Deposition (LPD) technique. Their research evaluated variations in sodium silicate concentration, temperature, and suspension pH to determine ideal synthesis conditions. The results indicated that a sodium silicate concentration of 0.1 mol/L, a temperature setting of 80 °C, and a pH level of 9.0 provided the most uniform and well-formed SiO_2 coatings on the α-Al_2O_3 particles. [77]

In a 2024 study, Cheraghipoor M et al. synthesized green copper-colored mica pearlescent pigments by coating mica with copper oxide films. Advanced characterization methods including X-ray Diffraction (XRD), X-ray Fluorescence (XRF), and Scanning Electron Microscopy (SEM) were employed to confirm the crystalline phases, elemental composition, and surface morphology of the pigments. Additionally, the researchers evaluated how these pigments dispersed in polypropylene and assessed their appearance in the polymer matrix, highlighting their potential for various industrial applications. [78]

2.1.4 Characterization of pearlescent pigments

In their 2005 study, Knoth et al. investigated zirconia/silica-based pearlescent pigments using a combination of X-ray diffraction (XRD) and transmission electron microscopy (TEM). Their research centered on understanding the structural and microstructural features, as well as the phase transformations occurring during pigment synthesis. The main objective was to optimize the luster and stability of these pigments while minimizing excessive grain growth during the sintering process—a factor crucial for maintaining their desirable optical properties. [79]

A separate investigation applied multiple advanced characterization techniques, employing X-ray Diffraction (XRD) to analyze the pigments' crystalline structure, Scanning Electron Microscopy (SEM) to observe surface features, and spectrophotometry to evaluate their optical reflectance and transmission properties. The results showed that the nanocrystalline films, once coated with a thin layer of silicon dioxide (SiO_2), exhibited vibrant interference colors and striking angle-dependent color effects—key attributes that contribute to the appealing and dynamic visual qualities of pearlescent pigments. [80]

Bergamonti L et al. underscored the value of Raman spectroscopy as a powerful, non-destructive analytical technique for differentiating natural pigments from synthetic dyes. This capability is crucial for cultural heritage applications and pigment analysis in various industrial contexts. [81]

To ensure high-quality TiO_2 coatings in pearlescent pigment production, multiple characterization techniques are employed. X-ray Diffraction (XRD) serves to reveal the crystal phases within the TiO_2 layers, helping to validate both the composition and the success of the deposition process. Meanwhile, Scanning Electron Microscopy (SEM) is utilized to capture detailed visuals of the pigment's surface, allowing for evaluation of texture and coating consistency. Optical microscopy (OM) adds a visual layer of analysis, offering additional insights into how the coatings are distributed on mica flakes. Finally, colorimetric measurements—usually performed with spectrophotometers—assess key optical properties such as brightness, color, and overall visual quality of the pigments. [82]

Further investigations have utilized UV-visible spectrophotometry to measure optical properties like reflectance and pearlescent effects. The emission of negative air ions was quantified using specialized ion measurement techniques, while antimicrobial tests evaluated the pigments' potential for inhibiting common indoor pathogens. Additionally, Fourier transform infrared spectroscopy (FTIR) was conducted to reveal chemical bonds and functional groups, offering insight into the pigments' chemical makeup. [83]

2.1.5 Optical properties of pearlescent pigments

Pigments' capacity to selectively absorb and reflect particular visible light wavelengths results in the vivid colors they generate. The degree to which pigments selectively reflect portions of the visible spectrum is expressed in terms of reflectance across the visible spectrum. Higher levels of reflectivity generally correlate with greater brightness and color saturation. [84]

In pearlescent pigments, the multilayer structure plays a critical role in defining their optical properties. These structures cause the incoming light to be partially scattered at the boundaries of the layers and partially reflected. The resulting effect is a gradual decrease in the intensity of the reflected light, giving rise to the characteristic pearl luster—an iridescent shine that seems to emerge from the coated surface itself. [33]

Some of the incident light passes through the translucent, glossy mica platelets in the pearlescent pigment. As this transmitted light encounters other boundaries with different refractive indices, parts of it are reflected again. These various reflections interfere with each other, creating the distinctive optical interference that underlies the shimmering pearlescent appearance, as shown in **Figure 8.** [23]

In contrast, organic pigments generally have a low refractive index and are composed of very fine particles—often significantly smaller than the wavelengths of visible light. This leads to reduced light scattering and renders organic pigments highly transparent in many cases. [85]

The visible chroma, color, and brightness of pearlescent pigments—which are typically created by coating translucent mica platelets with thin layers of metal oxides—are highly dependent on the angles of illumination and observation. [86] Certain complex inorganic pigments, particularly those comprising mixed metal oxides, also exhibit high near-infrared (NIR) reflectance while maintaining deep, dark hues in the visible spectrum. This dual capability of reflecting heat while displaying intense color makes them particularly well-suited for energy-efficient coatings in applications like cool roofs and architectural facades. [87]

Similar to mirrors, pearlescent and interference pigments reflect light specularly, creating dramatic visual effects. When these pigments are combined with conventional absorption pigments—whose reflections are diffuse and scattered—they produce unique color effects that blend optical phenomena with pigmentation. [88] Because the appearance of metallic and pearlescent pigments shifts with the viewing angle, specialized equipment is needed to accurately measure and quantify these dynamic effects. [89]

Extended films, extended coatings, and coatings containing specific effect pigments can also produce angle-dependent optical phenomena. Because they are easier to use and comparatively inexpensive when compared to alternative techniques, pearlescent and optical multilayer pigments are the most popular among them. [90]

Akinay Y and colleagues recently performed an in-depth characterization of mica-based pearlescent pigments. They used Field Emission Scanning Electron Microscopy (FESEM) to analyze surface morphology, Fourier-Transform Infrared Spectroscopy (FTIR) to investigate chemical bonding, and X-ray Diffraction (XRD) to examine crystal structures. Thermogravimetric Analysis (TGA) was employed to assess thermal stability, while Ultraviolet–Visible (UV–Vis) spectroscopy was used to evaluate optical performance. The team also conducted dielectric and electromagnetic wave absorption measurements, exploring potential applications of these pigments in electromagnetic interference shielding and related fields. [91]

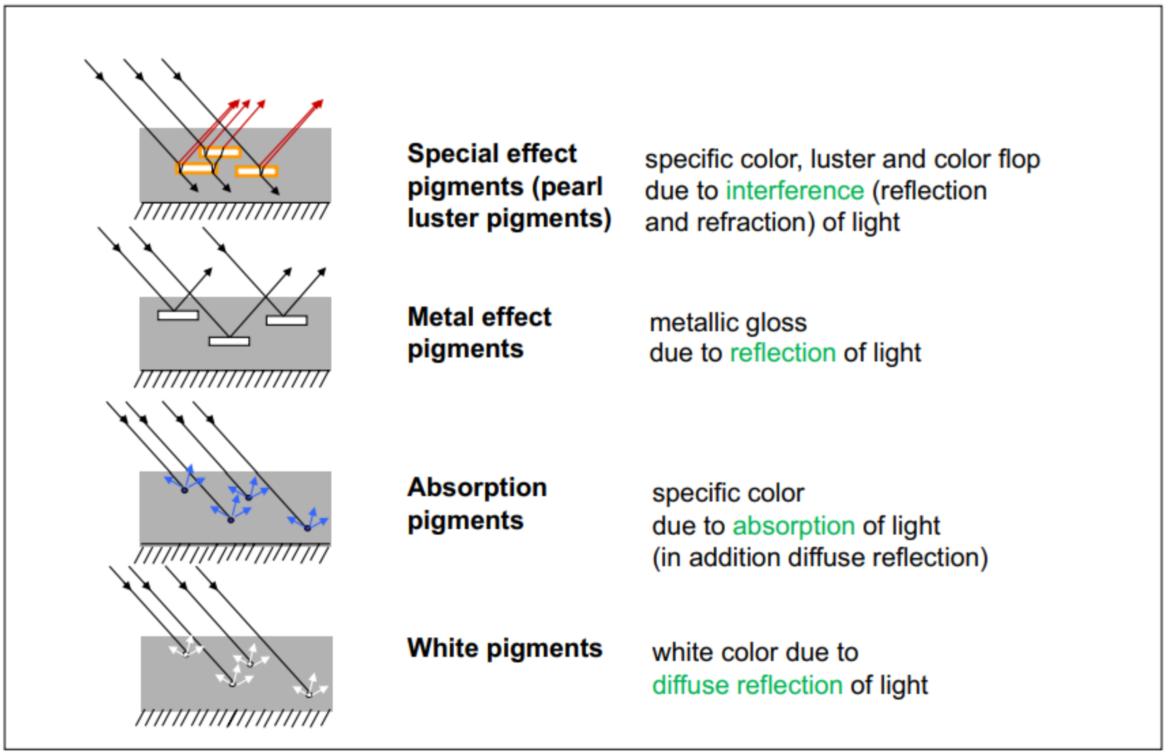

Figure 8: Visible light's optical interaction with various pigment particles in an application method, such a coating. [92]

2.1.6 Applications of pearlescent pigments

- **Pearlescent pigments** possess excellent light resistance, making them highly suitable for printed materials that are displayed outdoors or exposed to intense lighting conditions. [33]
- These pigments are often incorporated into textile coatings to improve protection against ultraviolet (UV) and infrared (IR) radiation. Typically containing titanium dioxide, they reduce UV transmission and reflect IR light, helping to manage light and heat exposure without compromising the inherent qualities of the textile. As a result, coatings with pearlescent pigments offer functional protection while preserving the textile's performance characteristics. [93]

- In the field of building-integrated photovoltaics (BIPV), pearlescent pigments are used to create colored glass with high light transmittance. By blending them with optical adhesives and spin-coating them onto glass surfaces, these pigments enable the creation of color-customizable BIPV panels that maintain more than 85% light transmittance. This approach adds an attractive visual element to solar panels while preserving their efficiency and energy generation capacity. [94]
- Specially coated mica particles act as pearlescent pigments in makeup and cosmetic products, producing a shimmering, appealing effect. In addition to cosmetics, these pigments are used in paints, inks, surface coatings, plastics, glass, ceramics, textile printing, laser marking coatings, and barrier-type corrosion protection, providing a combination of aesthetic appeal and practical improvements. [95]
- In the food industry, pigments containing titanium dioxide (TiO_2) are used to impart a shiny, glittery, or pearlescent appearance to various products. These pigments, which are authorized food additives in the European Union where TiO_2 is recognized as E 171, often consist of mica platelets covered with titanium dioxide and/or iron oxides. [96]
- Another important application lies in improving color quality control during printing processes that utilize pearlescent pigments. The integration of simple camera-based setups can allow for faster and more precise measurement of color, aiding in the creation of high-quality, consistent prints. [97]

2.1.7 Research Gap

Although pearlescent pigments have found widespread applications in cosmetics, automotive coatings, and packaging, several important gaps persist in current research. Much of the existing work has focused on traditional metal oxides like TiO_2 and Fe_2O_3, yet little progress has been made toward optimizing low-temperature, energy-efficient synthesis methods—particularly those that avoid calcination and support rutile-phase formation. Additionally, while novel doped systems and hybrid coatings have been developed, comprehensive studies on their scalability, substrate compatibility, and long-term stability are still lacking.

A particularly promising yet underexplored area is the synthesis of pearlescent pigments using metal nanoparticles such as silver, gold, copper, and platinum. These nanoparticles can offer tunable plasmonic effects, enhanced brightness, and improved thermal and chemical resistance. Their incorporation into pigment systems could lead to new optical functionalities, including improved reflectivity, antimicrobial properties, and enhanced electromagnetic shielding. However, challenges remain in controlling their dispersion, avoiding aggregation, and ensuring environmental safety.

Furthermore, standardized methods for quantifying angle-dependent optical effects are insufficient, hindering consistent quality assessment. Functional applications—such as in BIPV panels, smart coatings, and food-contact materials—remain in their infancy and require more interdisciplinary study. Bridging these gaps could unlock sustainable, multifunctional pigment technologies for next-generation industrial applications.

CHAPTER 3

3.1 Conclusion

Pearlescent pigments have evolved into indispensable components in various industrial and commercial sectors, celebrated for their unique optical features, including luster, angle-dependent color shifts, and chromatic brilliance. This review has explored their structural foundations, synthesis techniques, and the influence of metal oxides such as titanium dioxide, iron oxide, and zinc oxide in generating optical effects through thin-film interference. These pigments not only serve decorative purposes in cosmetics, automotive, and packaging applications but also offer functional advantages like UV resistance and thermal stability.

Advanced characterization tools such as XRD, SEM, UV-Vis, and FTIR have proven essential for understanding the morphology, phase, and optical behavior of these complex materials. However, current practices rely heavily on energy-intensive processes and non-renewable raw materials, posing environmental and regulatory challenges. Despite significant technological progress, limitations persist in phase control, reproducibility, and large-scale processing.

The review also highlights the increasing interest in hybrid pigments, metal nanoparticle incorporation, and low-temperature synthesis techniques. These innovations have the potential to expand functional uses while addressing environmental concerns. Overall, pearlescent pigments continue to offer immense potential across both aesthetic and technical domains, underscoring the need for ongoing interdisciplinary research to enhance their sustainability, safety, and performance in evolving industrial contexts.

3.2 Future Scope

The future of pearlescent pigment technology lies at the intersection of aesthetic innovation, functional enhancement, and environmental sustainability. A promising direction involves the synthesis of pigments using metal nanoparticles such as silver, gold, and copper, which offer tunable plasmonic properties, improved UV resistance, and antimicrobial functions. These advanced materials could significantly expand the role of pigments beyond decorative applications to include electronics, sensors, and smart coatings.

In terms of manufacturing, transitioning from high-temperature calcination to low-energy wet-chemical or sol-gel techniques presents an opportunity to reduce the carbon footprint of pigment production. Moreover, the use of biodegradable or bio-derived substrates instead of traditional mica could further support the shift toward sustainable development.

Another important future direction is the integration of smart characterization systems, particularly angle-resolved and hyperspectral imaging technologies, to quantify optical anisotropy with precision. This will greatly benefit industries where color consistency and dynamic appearance are critical.

From a regulatory perspective, developing pigments that meet stringent health and safety standards—especially for food, cosmetics, and medical packaging—will be essential. The growing demand for multifunctional materials ensures that pearlescent pigments will remain a focal point for innovation. Future research should aim for holistic solutions that blend optical excellence with ecological responsibility.

3.4 References

[1] S. Rossi and F. Russo, "Pearlescent Pigments: history, properties and application in powder coatings," Mar. 24, 2020. doi: 10.32545/encyclopedia202003.0004.v1.

[2] T. A. Germer and M. E. Nadal, "Modeling the appearance of special effect pigment coatings," 2001.

[3] W. S. Czajkowski, "Organic pigments," in *Modern Colorants: Synthesis and Structure*, Dordrecht: Springer Netherlands, 1995, pp. 63–86. doi: 10.1007/978-94-011-1356-4_3.

[4] B. DA. Otterstedt J-E, "Pigments. Small Particles Technology".

[5] "Oil and Colour Chemists' Association. Inorganic Pigments in Surface Coatings ".

[6] G. Pfaff, K. Franz, K. Emmert, and R. Nitta, "Pigments, Inorganic. In Ullmann's Encyclopedia of Industrial Chemistry, 6th ed.".

[7] M. Jansen and H. P. Letschert, "Inorganic yellow-red pigments without toxic metals," *Nature*, vol. 404, no. 6781, pp. 980–982, Apr. 2000, doi: 10.1038/35010082.

[8] J. Guo, Y. Chen, Y. Guo, and J. Pan, "A Physically-based Appearance Model for Special Effect Pigments," *Computer Graphics Forum*, vol. 37, no. 4, pp. 67–76, Jul. 2018, doi: 10.1111/cgf.13476.

[9] S. Eivazi, "How to get changing patterns on a textile surface by using pearl luster and color travel pigments."

[10] S. Rossi, F. Russo, and L. B. Rahmani, “Study of the durability and aesthetical properties of powder coatings admixed with pearlescent pigments,” *Coatings*, vol. 10, no. 3, Mar. 2020, doi: 10.3390/coatings10030229.

[11] B. Mahltig *et al.*, “Effect pigments for textile coating: a review of the broad range of advantageous functionalization,” *J Coat Technol Res*, vol. 14, no. 1, pp. 35–55, Jan. 2017, doi: 10.1007/s11998-016-9854-9.

[12] H. Shiomi, E. Misaki, M. Adachi, and F. Suzuki, “High chroma pearlescent pigments designed by optical simulation,” *J Coat Technol Res*, vol. 5, no. 4, pp. 455–464, 2008, doi: 10.1007/s11998-008-9085-9.

[13] K. Topp, H. Haase, C. Degen, G. Illing, and B. Mahltig, “Coatings with metallic effect pigments for antimicrobial and conductive coating of textiles with electromagnetic shielding properties,” *J Coat Technol Res*, vol. 11, no. 6, pp. 943–957, Nov. 2014, doi: 10.1007/s11998-014-9605-8.

[14] M. Matejdes, J. Hausner, M. Grüner, G. Kaupp, and J. Breu, “ABSORPTION PIGMENT CORES FOR PEARLESCENT PIGMENTS,” *Clays Clay Miner*, vol. 68, no. 5, pp. 428–435, Oct. 2020, doi: 10.1007/s42860-020-00085-7.

[15] A. R. Mirhabibi, “Ceramic Coatings for Pigments,” in *Ceramic Coatings - Applications in Engineering*, InTech, 2012. doi: 10.5772/30010.

[16] F. J. Maile, G. Pfaff, and P. Reynders, “Effect pigments - Past, present and future,” Nov. 01, 2005. doi: 10.1016/j.porgcoat.2005.07.003.

[17] P. Pelicon, M. Klanjšek-Gunde, M. Kunaver, J. Simčič, and M. Budnar, “Analysis of metallic pigments by ion microbeam,” *Nucl Instrum Methods Phys Res B*, vol. 190, no. 1–4, pp. 370–374, May 2002, doi: 10.1016/S0168-583X(01)01213-7.

[18] E. J. J. Kirchner, G. J. van den Kieboom, L. Njo, R. Supèr, and R. Gottenbos, "Observation of visual texture of metallic and pearlescent materials," *Color Res Appl*, vol. 32, no. 4, pp. 256–266, Aug. 2007, doi: 10.1002/col.20328.

[19] R. Shackleton and G. Wendon, "Developments in metallic pigments," *Pigment & Resin Technology*, vol. 1, no. 9, pp. 27–30, Sep. 1972, doi: 10.1108/eb040846.

[20] F. J. Maile, G. Pfaff, and P. Reynders, "Effect pigments - Past, present and future," Nov. 01, 2005. doi: 10.1016/j.porgcoat.2005.07.003.

[21] C. S. Mccamy, "Observation and Measurement of the Appearance of Metallic Materials. Part II. Micro Appearance," 1998.

[22] Rodrigues and Allan BJ., "Color and appearance measurement of metallic and pearlescent finishes.".

[23] M. E. Nadal and E. A. Early, "Color Measurements for Pearlescent Coatings," *Color Res Appl*, vol. 29, no. 1, pp. 38–42, 2004, doi: 10.1002/col.10210.

[24] R. M. Christie, "Pigments for plastics."

[25] B. Sarkodie, C. Acheampong, B. Asinyo, X. Zhang, and B. Tawiah, "Characteristics of pigments, modification, and their functionalities," Jun. 01, 2019, *John Wiley and Sons Inc.* doi: 10.1002/col.22359.

[26] R. A. Charvat, "COLORING OF PLASTICS Fundamentals Second Edition," 2004. [Online]. Available: www.copyright.com.

[27] P. M. Tenório Cavalcante, M. Dondi, G. Guarini, F. M. Barros, and A. Benvindo da Luz, "Ceramic application of mica titania pearlescent pigments," *Dyes and Pigments*, vol. 74, no. 1, pp. 1–8, 2007, doi: 10.1016/j.dyepig.2006.01.026.

[28] G. Pfaff, “Special Effect Pigments, In: High Performance Pigments”.

[29] Ram Charan, “Application, Characteristics and Information of Pearl Pigments, Product Development information, Vol. 3, No. 4, July 2013. ”.

[30] M. Gajadhur and A. Łuszczyńska, “Influence of pearlescent pigments on light-fastness of water-based flexographic inks,” *Dyes and Pigments*, vol. 138, pp. 119–128, Mar. 2017, doi: 10.1016/j.dyepig.2016.11.033.

[31] I. Tomić, R. Szentgyörgyvölgyi, S. Dedijer, and D. ; J. I. Novaković, “Tomić, I.; DediLightfastness of Goniochromatic Prints. IJCELIT 2017”.

[32] G. A. Klein, “Industrial Color Physics. 2010.”.

[33] “Pearlescent pigments in printing,” 2018. [Online]. Available: https://www.researchgate.net/publication/325896991

[34] H. M. Smith, Ed., *High Performance Pigments*. Wiley, 2001. doi: 10.1002/3527600493.

[35] L. C. Greiler, A. Schwarz-Pfeiffer, and B. Mahltig, “Pearlescent Effect Pigments for Coatings on Textiles-Part II: Angle Dependent Coloration,” 2021. [Online]. Available: https://www.researchgate.net/publication/365276014

[36] “pfaff2003”.

[37] R. Maisch, O. Stahlecker, and M. Kieser, “PROGRESS ’%WF Mica pigments in solvent free coatings systems,” 1996.

[38] V. Štengl, J. Šubrt, S. Bakardjieva, A. Kalendova, and P. Kalenda, “The preparation and characteristics of pigments based on mica coated with metal oxides,” *Dyes and Pigments*, vol. 58, no. 3, pp. 239–244, 2003, doi: 10.1016/S0143-7208(03)00086-X.

[39] J. Gambogi, “USGS Mineral Commodities Summary Report. ”.

[40] P. M. Kuznesof, “Titanium Dioxide — Chemical and Technical Assessment.”.

[41] S. Yuan and W. Chen, “ Fabrication of TiO2 nanoparticles/surfactant polymer complex film on glassy carbon electrode. Mater. Sci. Eng.”.

[42] B. Kaur and S. N. Bhattacharya, “Automotive dyes and pigments,” in *Handbook of Textile and Industrial Dyeing*, Elsevier, 2011, pp. 231–251. doi: 10.1533/9780857094919.2.231.

[43] S. Middlemas, Z. Z. Fang, and P. Fan, “A new method for production of titanium dioxide pigment,” *Hydrometallurgy*, vol. 131–132, pp. 107–113, 2013, doi: 10.1016/j.hydromet.2012.11.002.

[44] G. B. Song, J. K. Liang, F. S. Liu, T. J. Peng, and G. H. Rao, “Preparation and phase transformation of anatase–rutile crystals in metal doped TiO2/muscovite nanocomposites,” *Thin Solid Films*, vol. 491, no. 1–2, pp. 110–116, Nov. 2005, doi: 10.1016/j.tsf.2005.05.035.

[45] Jr. C.A. DeLuca and L.R. Cerce, “ Jr., U.S. Patent 6,626,989. (2003)”.

[46] E. B. Faulkner and R. J. Schwartz, Eds., *High Performance Pigments*. Wiley, 2009. doi: 10.1002/9783527626915.

[47] S. Rasouli, S. Saket, and M. Safi, “Preparation of Bronze Pearlescent Pigment by Using Unsupported Mica-Titania,” 2010.

[48] K. K. Sahu, T. C. Alex, D. Mishra, and A. Agrawal, “An overview on the production of pigment grade titania from titania-rich slag,” *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 24, no. 1, pp. 74–79, Feb. 2006, doi: 10.1177/0734242X06061016.

[49] P. Gabel and G. Pfaff, "4 Characterisation of pearlescent pigments and special effect pigments."

[50] B. B. Topuz, G. Gündüz, B. Mavis, and Ü. Çolak, "The effect of tin dioxide (SnO2) on the anatase-rutile phase transformation of titania (TiO2) in mica-titania pigments and their use in paint," *Dyes and Pigments*, vol. 90, no. 2, pp. 123–128, Aug. 2011, doi: 10.1016/j.dyepig.2010.12.013.

[51] M. Hosseini-Zori, "A r c h i v e o f S I D Synthesis and Characterization of Red Pearlescent Pigments Based on Muscovite and Zirconia-Nanoencapsulated Hematite," 2012. [Online]. Available: www.pccc.icrc.ac.ir

[52] G. Pfaff and P. Reynders, "Angle-Dependent Optical Effects Deriving from Submicron Structures of Films and Pigments," *Chem Rev*, vol. 99, no. 7, pp. 1963–1982, Jul. 1999, doi: 10.1021/cr970075u.

[53] A. García, "Effect of the surfactant and precipitant on the synthesis of pink coral by a microemulsion method," *J Eur Ceram Soc*, vol. 23, no. 11, pp. 1829–1838, Oct. 2003, doi: 10.1016/S0955-2219(02)00451-X.

[54] M. Hosseini-Zori, "Particle size and kind of mica in synthesis of nontoxic bronze and gold pearlescent pigments based on nanoencapsulated hematite," *Journal of Ultrafine Grained and Nanostructured Materials*, vol. 48, no. 2, pp. 101–112, 2015, doi: 10.7508/jufgnsm.2015.02.005.

[55] F. Bondioli, T. Manfredini, C. Siligardi, and A. M. Ferrari, "New Glass–Ceramic Inclusion Pigment," *Journal of the American Ceramic Society*, vol. 88, no. 4, pp. 1070–1071, Apr. 2005, doi: 10.1111/j.1551-2916.2005.00217.x.

[56] M. HOSSEINIZORI, F. BONDIOLI, T. MANFREDINI, and E. TAHERINASSAJ, “Effect of synthesis parameters on a hematite–silica red pigment obtained using a coprecipitation route,” *Dyes and Pigments*, vol. 77, no. 1, pp. 53–58, 2008, doi: 10.1016/j.dyepig.2007.03.006.

[57] H. Heydari, R. Naghizadeh, H. R. Samimbanihashemi, and M. Hosseini-Zori, “Synthesis and Characterisation of Hematite-Zircon Nanocomposite by Sol-Gel Method,” *Adv Mat Res*, vol. 829, pp. 544–548, Nov. 2013, doi: 10.4028/www.scientific.net/AMR.829.544.

[58] X. Liang, H. Xu, J. Chen, J. Sun, Y. Yang, and X. Liu, “Research of mica/Fe3O4 pearlescent pigment by co-precipitation,” *Glass Physics and Chemistry*, vol. 37, no. 3, pp. 330–342, Jun. 2011, doi: 10.1134/S1087659611030084.

[59] W. M. A. El-Gawad, E. A. Mossalam, and M. M. Selim, “Facile preparation of anticorrosive and decorative multifunctional coatings via the inclusion of pearlescent oxide-covered mica pigments,” *J Coat Technol Res*, vol. 20, no. 2, pp. 603–622, Mar. 2023, doi: 10.1007/s11998-022-00693-z.

[60] P. Karlsson, A. E. C. Palmqvist, and K. Holmberg, “Surface modification for aluminium pigment inhibition,” *Adv Colloid Interface Sci*, vol. 128–130, pp. 121–134, Dec. 2006, doi: 10.1016/j.cis.2006.11.010.

[61] T. Uchiyama, M. Hasegawa, and H. M. T. Ootsuka, “Process for preparing colored aluminum powder”.

[62] W. Ostertag, G. ; Knut Bittler, and G. Bock, “United States Patent (19) Ostertag et al. 54 PREPARATION OF METALLIC PIGMENTS HAVING A METALLIC LUSTER 75) Inventors.”

[63] Y. Zhang, H. Ye, and H. Liu, “Preparation and characterization of blue color aluminum pigments Al/SiO 2/PB with double-layer structure,” *Powder Technol*, vol. 217, pp. 614–618, Feb. 2012, doi: 10.1016/j.powtec.2011.11.035.

[64] R. Schoppe, “Aluminum Pigments for Plastics.”

[65] R. et al. Schmid, “‘Optisch variable Glanzpigmente. Diskussion. Autor’s antwort.’ ”.

[66] R. Maisch and M. Weigand, “Verlag Moderne Industrie.”.

[67] C. S. McCamy, “Observation and measurement of the appearance of metallic materials. Part I. Macro appearance,” *Color Res Appl*, vol. 21, no. 4, pp. 292–304, Aug. 1996, doi: 10.1002/(SICI)1520-6378(199608)21:4<292::AID-COL4>3.0.CO;2-L.

[68] H. J. A. Saris, R. J. B. Gottenbos, and H. Van Houwelingen, “Correlation between visual and instrumental colour differences of metallic paint films,” *Color Res Appl*, vol. 15, no. 4, pp. 200–205, Aug. 1990, doi: 10.1002/col.5080150405.

[69] E. Chorro, E. Perales, F. M. Martinez-Verdu, J. Campos, and A. Pons, “Colorimetric and spectral evaluation of the optical anisotropy of metallic and pearlescent samples,” *J Mod Opt*, vol. 56, no. 13, pp. 1457–1465, Jul. 2009, doi: 10.1080/09500340903171706.

[70] L. Armanini, “Basic optics and Pearlescent Pigments,” Oct. 01, 1988. doi: 10.1108/eb042537.

[71] A. Mirhabibi, M. Esfidari, and R. Aghababazadeh, “Synthesis of gold pearlescent pigment via heat treatment of mica,” *J Coat Technol Res*, vol. 5, no. 1, pp. 73–76, 2008, doi: 10.1007/s11998-007-9048-6.

[72] T. G. Kim *et al.*, “Phase Transformation of TiO_2 in the Preparation of Pearlescent Pigment,” *Materials Science Forum*, vol. 544–545, pp. 99–102, May 2007, doi: 10.4028/www.scientific.net/msf.544-545.99.

[73] Q. Gao, X. Wu, Y. Fan, and X. Zhou, “Low temperature synthesis and characterization of rutile TiO 2-coated mica-titania pigments,” *Dyes and Pigments*, vol. 95, no. 3, pp. 534–539, Dec. 2012, doi: 10.1016/j.dyepig.2012.06.006.

[74] C. Jing and S. X. Hanbing, “The preparation and characteristics of cobalt blue colored mica titania pearlescent pigment by microemulsions,” *Dyes and Pigments*, vol. 75, no. 3, pp. 766–769, 2007, doi: 10.1016/j.dyepig.2006.08.020.

[75] M. Cheraghipoor and M. Zakeri, “Incorporation of Metal Oxides on Mica Flakes as Green Pearlescent Pigments: Preparation and Analysis,” *Iranian Journal of Chemical Engineering*, vol. 17, no. 2, pp. 34–43, 2020, doi: 10.22034/ijche.2020.234719.1339.

[76] S. A. Hassanzadeh-Tabrizi, “Influences of Cr content and heat treatment on the optical property of the green mica-nano Cr2O3 pearlescent pigment,” *J Coat Technol Res*, vol. 12, no. 4, pp. 751–756, Jul. 2015, doi: 10.1007/s11998-015-9664-5.

[77] N. Wu, Q. H. Chen, W. M. Zhou, M. Z. Ke, Q. R. Qian, and Z. H. Yuan, “An exploration of factors affecting the preparation of SiO2-coated α-Al2O3 pearlescent pigment,” in *Advanced Materials Research*, Trans Tech Publications Ltd, 2014, pp. 26–29. doi: 10.4028/www.scientific.net/AMR.983.26.

[78] M. Cheraghipoor, M. Zakeri, H. Moghadam, and M. Samimi, “A Feasibility Study for the Preparation of Green Copper-Colored Mica Pearlescent Pigments,” *Advanced Journal of Chemistry, Section A*, vol. 7, no. 3, pp. 338–346, May 2024, doi: 10.48309/ajca.2024.436923.1480.

[79] M. Knoth, G. Miehe, and H. Fuess, "Characterization of pearl luster pigments," Oct. 2005. doi: 10.1002/adem.200500115.

[80] S. Bertaux, P. Reynders, J. M. Heintz, and M. Lerch, "New (oxy)nitride pearlescent pigments," *Materials Science and Engineering: B*, vol. 121, no. 1–2, pp. 137–144, Jul. 2005, doi: 10.1016/j.mseb.2005.03.029.

[81] L. Bergamonti, D. Bersani, D. Csermely, and P. P. Lottici, "The nature of the pigments in Corals and Pearls: A contribution from Raman spectroscopy," in *Spectroscopy Letters*, Taylor and Francis Inc., 2011, pp. 453–458. doi: 10.1080/00387010.2011.610399.

[82] N. Bayat, S. Baghshahi, and P. Alizadeh, "Synthesis of white pearlescent pigments using the surface response method of statistical analysis," *Ceram Int*, vol. 34, no. 8, pp. 2029–2035, Dec. 2008, doi: 10.1016/j.ceramint.2007.07.034.

[83] A. Aslan, E. Karaduman, E. M. Derun, and M. B. Piskin, "Development and characterization of negative air ion emitting mica- and sericite-based antimicrobial pearlescent pigments," *Ceram Int*, vol. 47, no. 18, pp. 26421–26429, Sep. 2021, doi: 10.1016/j.ceramint.2021.06.053.

[84] T. Junru, F. Xiansong, H. Wenxiang, C. Xiuzeng, and W. Li, "The preparation and characteristics of a multi-cover-layer type, blue mica titania, pearlescent pigment." [Online]. Available: www.elsevier.com/locate/dyepig

[85] R. M. Christie, "Pigments, Dyes and Fluorescent Brightening Agents for Plastics: an Qverview," 1994.

[86] M. E. Nadal and T. A. Germert, "Colorimetric characterization of pearlescent coatings," 2002. [Online]. Available: http://proceedings.spiedigitallibrary.org/

[87] R. Levinson, P. Berdahl, and H. Akbari, "Solar spectral optical properties of pigments - Part II: Survey of common colorants," *Solar Energy Materials and Solar Cells*, vol. 89, no. 4, pp. 351–389, Dec. 2005, doi: 10.1016/j.solmat.2004.11.013.

[88] Armanini, Louis, and Henry L. Mattin, "Three Color Effects From Interference Pigments.".

[89] B. D. Teunis, "Multi-Angle Spectrophotometers for Metallic, Pearlescent, and Special Effects Colors".

[90] H. Du, C. Liu, J. Sun, and Q. Chen, "An investigation of angle-dependent optical properties of multi-layer structure pigments formed by metal-oxide-coated mica," *Powder Technol*, vol. 185, no. 3, pp. 291–296, Jul. 2008, doi: 10.1016/j.powtec.2007.10.031.

[91] Y. Akinay and I. Nuri Akkuş, "Synthesis and characterization of the pearlescent pigments based on mica deposited with SiO2, AlN and TiO2: First report of its dielectric properties," *Ceram Int*, vol. 46, no. 11, pp. 17735–17740, Aug. 2020, doi: 10.1016/j.ceramint.2020.04.078.

[92] G. Pfaff, "The world of inorganic pigments," Aug. 01, 2022, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s40828-022-00166-1.

[93] L. C. Greiler and B. Mahltig, "Pearlescent Effect Pigments for Coatings on Textiles-Part I: Protective Materials Against UV Light and IR Light," 2021. [Online]. Available: https://www.researchgate.net/publication/365275708

[94] H. S. Ahn, A. Gasonoo, S. M. Lim, J. H. Lee, and Y. Choi, "Fabrication of Color Glass with High Light Transmittance by Pearlescent Pigments and Optical Adhesive," *Materials*, vol. 15, no. 7, Apr. 2022, doi: 10.3390/ma15072627.

[95] Y. Huang, Y. Yang, W. Huan, H. Yuan, L. Wang, and R. Carlini, "Preparation of Magnetic Pearlescent Pigment Mica/Fe3O4 by Thermally Decomposing Ferric Formate Composite Containing Hydrazine," *J Inorg Organomet Polym Mater*, vol. 28, no. 3, pp. 651–670, May 2018, doi: 10.1007/s10904-017-0719-1.

[96] B. Hetzer, V. Gräf, E. Walz, and R. Greiner, "Characterisation of TiO2-containing pearlescent pigments with regard to the European Union labelling obligation of engineered nanomaterials in food," *Food Addit Contam Part A Chem Anal Control Expo Risk Assess*, vol. 38, no. 5, pp. 741–753, 2021, doi: 10.1080/19440049.2021.1901998.

[97] I. Tomić, S. Dedijer, D. Novaković, and I. Jurič, "Artificial neural networks for optimising camera-based colour measurements of prints enhanced with pearlescent pigments," *Coloration Technology*, vol. 134, no. 5, pp. 364–372, Oct. 2018, doi: 10.1111/cote.12346.

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering Bawana Road, Delhi-110042)

PLAGIARISM VERIFICATION

Title of the Thesis "**Advances in Pearlescent Pigments: Structure, Synthesis, and Sustainability**"

Total Pages: **54**, Name of the Student: **Sonia Mawri**

Supervisor (s)

(1) Prof. Roli Purwar

Department **Applied Chemistry**

This is to report that the above thesis was scanned for similarity detection. Process and outcome is given below:

Software used: **Turnitin** , Similarity Index:**8%** , Total Word Count: **10,481**

Date: 20-06-2025

Candidate's Signature   Signature of Supervisor(s)

PLAGIARISM REPORT

Sonia

SONIA.pdf

Delhi Technological University

Document Details

Submission ID

trn:oid:::27535:101660197

Submission Date

Jun 19, 2025, 4:00 PM GMT+5:30

Download Date

Jun 19, 2025, 4:04 PM GMT+5:30

File Name

SONIA.pdf

File Size

1.9 MB

47 Pages

10,481 Words

62,184 Characters

8% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Small Matches (less than 8 words)

Match Groups

- **49** Not Cited or Quoted 7%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **3** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

- 5% Internet sources
- 5% Publications
- 3% Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.