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Exploring the Therapeutic Potential of Microbial Pigments: A Comprehensive Review

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Review Article

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ABSTRACT

Microbial pigments have emerged as promising candidates in various fields due to their diverse therapeutic properties, encompassing antibacterial, anticancer, cytotoxic and antioxidant activities. This comprehensive review explores their applications in medicine, industry, and environmental sustainability. Through an in-depth analysis of literature and research findings, we elucidate the significant contributions of microbial pigments across multiple domains, including healthcare, food production, textile manufacturing, agriculture, and water science. Additionally, we highlight the contrast between natural pigments and synthetic counterparts, emphasizing the urgent need for sustainable alternatives. By examining the therapeutic potential of microbial pigments, this review aims to inspire further research and innovation, promoting their utilization for the betterment of human health and the environment.

Keywords: Microbial pigments; Therapeutic potential; Antibacterial; Anticancer; Cytotoxic; Antioxidant; Medicine, Industry; Environmental sustainability; Natural pigments; Synthetic pigments; Biomedical applications; Sustainable alternatives

INTRODUCTION

The development and adoption of bio-colours, derived from natural sources including microbial pigments, signify a market movement towards sustainable and eco-friendly alternatives. This shift is driven by the growing demand for nutraceutical products with advantageous qualities, highlighting the importance of exploring natural sources of food-grade colorants and their potential applications in various industries.

In particular, they look for unusual colours like blue in naturally occurring plants, animals, microscopic fungus, and microorganisms. The food and beverage industries hunt for all natural colorants. This is a result of the growing interest in recent times about consuming natural substances. Promising chemicals exhibiting bioactivities in pigments have also been developed as a result of the necessity to find novel antibiotics to combat the emergence of new developing infections and strains exhibiting antimicrobial resistance. Furthermore, a number of artificial colorants have been disqualified due to their hyper allergenicity or carcinogenicity, which has increased research on organic compounds [1].The food substance color serves as a key indicator of both its safety and freshness, as well as good aesthetic and sensory qualities. The practice of coloring food with natural pigments has gained popularity and global attention in recent years. Because of the unfavorable market, these pigments are regarded for their safe use as natural food dyes in substitution of synthetic ones. A food that is flavorful, nutritious, and well-textured cannot be consumed unless it is the correct color. Because more people are becoming aware of the beneficial effects that natural compounds have on their health, there is an increased need for natural sources of these compounds. Investigating other natural sources of food-grade colorants and their potential is therefore essential. Microbial colorants are widely used as food coloring agents due to their easy down-streaming process and ease of manufacture, even though there are numerous natural colors accessible. Natural food colorants can be produced industrially *via* microbial fermentation, which offers several benefits including reduced production costs, simpler extraction processes, and increased yields due to strain enhancement, no shortage of raw materials, and no seasonal changes.

The products color is one of its most important visual characteristics. Colors impact acceptability and provide anything that can be sold a desirable quality. Colors have been employed since ancient times to aid in the creation of many products, both to improve their appearance and to make up for natural color loss during processing. People tend to associate colors with different aspects of products, such as flavor, freshness, and taste. Since then, colors have emerged as a highly effective sensory assessment tool for product quality. Several industries, including food, cosmetics, textiles, and medicines, heavily rely on artificial synthetic hues. Even though synthetic dyes are more cost-effective and dependable than natural colors, they pose a serious risk to environmental preservation. Consequently, due to their toxicological issues, many synthetic colors are no longer allowed for usage. Natural pigments have been the subject of extensive investigation due to the terrible impacts of manufactured dyes. Because of this, a movement in the market has been considered toward the development and creation of bio-colors. This change in the market is mostly due to the neoteric development of nutraceutical products, such as bio-color, which are known to have numerous advantageous qualities.

Pathogenicity of pigmented microbes

Certain microbial pigments have been associated with increased pathogenicity and virulence, despite their potential therapeutic applications in various fields. For instance, *Pseudomonas aeruginosa*, known for producing the green pigment pyocyanin, demonstrates enhanced pathogenicity on sheep blood agar, often exhibiting high beta hemolysis. *Vibrio campbellii*, a significant pathogen within the *Vibrio harveyi* lineage, produces a brown pigment possibly attributed to pyomelanin or proteorhodopsin, contributing to its virulence. Phenazines produced by Pseudomonad species are also recognized for their role in pathogenicity [2].

Melanin synthesis has been linked to the virulence of bacterial species like *Vibrio cholerae* and fungal species like *Cryptococcus neoformans* and *Aspergillus fumigatus*, affecting their pathogenicity towards animal or plant hosts. *Mycobacterium marinum* and certain *Bacillus* species are known pathogens causing skin and soft tissue infections. *Serratia marcesens* is a well-known cause of nosocomial infections in the urinary system and wounds. Other pigmented substances associated with virulence activities include staphyloxanthin produced by *Staphylococcus aureus*, porphyrin generated by *Porphyromonas gingivalis*, and granadaene produced by *Streptococcus agalactiae*. *Chromobacterium violaceum*, producing violacein, is an opportunistic pathogen causing lethal septicemia and abscesses. Orange pigmentation in *Stenotrophomonas maltophilia* has also been identified, contributing to its pathogenicity in humans. Phytopathogenic bacteria like *Xanthomonas campestris* cause illnesses in vegetables like rutabagas, cauliflower, and cabbage. Salmonid fish furunculosis is attributed to melanin-like chemicals produced by *Aeromonas salmonicida*. Additionally, chronic lung infections, especially in cystic fibrosis patients, are caused by the pigmented exotoxin pyocyanine produced by *Pseudomonas aeruginosa*. These examples underscore the complex relationship between microbial pigments and pathogenicity, highlighting the need for further research to understand their mechanisms and implications in disease progression.

Therapeutic properties

The therapeutic potential of microbial pigments lies in their remarkable bioactivities, which include antibacterial, anticancer, cytotoxic, and antioxidant properties. Studies have shown that these pigments possess strong antibacterial activity against a wide range of pathogens, making them promising candidates for the development of novel antimicrobial agents. Additionally, microbial pigments have demonstrated anticancer properties by inducing apoptosis and inhibiting the proliferation of cancer cells. Their cytotoxic effects have been observed in various cancer cell lines, highlighting their potential as chemotherapeutic agents. Furthermore, microbial pigments exhibit exceptional antioxidant activity, scavenging free radicals and protecting cells from oxidative damage. These therapeutic properties make microbial pigments valuable assets in the fields of medicine, industry, and environmental sustainability [3].

This review aims to comprehensively explore the applications of microbial pigments in medicine, industry, and environmental sustainability. By examining the current literature and research findings, we seek to elucidate the significant contributions of microbial pigments across these diverse fields. Through a thorough analysis, we aim to highlight the potential of microbial pigments as therapeutic agents and sustainable alternatives to synthetic compounds. Ultimately, this review aims to inspire further research and innovation in utilizing the therapeutic potential of microbial pigments for the betterment of human health and the environment.

LITERATURE REVIEW

The superior health benefits of natural pigments over synthetic alternatives, including pharmacological advantages, have led to an increase in their market share. In daily life, pigments, colorants, and dyes extracted from natural sources find widespread utilization, such as in the production of food, paper, textiles, and agriculture. The adoption of green technology favours the use of natural and less hazardous materials in production, driven by concerns over the carcinogenic precursor products and environmental impact of industrial waste disposal associated with synthetic dyes and colorants, leading to their market bans. The trend towards natural sources for colouring chemicals stems from concerns about environmental safety, conservation, and increasing awareness. Natural dyes and colorants sourced from flora and fauna are preferred due to their non-toxicity, biodegradability, and non-carcinogenicity. Traditionally used natural colouring agents like anthraquinones and flavonoids, sourced mainly from plants and animals, are now driving market demand as the trend shifts towards eco-friendly components [4].

Microbial pigments have emerged as significant contributors to various industries, including textiles, natural products, food, and medicine, due to their remarkable qualities. Natural microbial pigments are highly sought after for their ability to produce necessary pigments in large quantities, environmental friendliness, lack of negative effects, biodegradability, ease of cultivation, stability, adaptability to different environments, and suitability for optimization and genetic engineering. These pigments play vital roles in biomedical, evolutionary, ecological, industrial, and agricultural research. Microbial pigments have been extensively studied for their diverse applications across various fields. A thorough literature search reveals their significant contributions to medicine, food production, textile manufacturing, agriculture, and water science.

Medicine

Microbial pigments have shown promising potential in medicine, particularly in the areas of antibacterial, anticancer, and antioxidant therapies. Studies have highlighted the antibacterial activity of pigments produced by microorganisms such as *Streptomyces* sp., *Bacillus* sp., and *Pseudomonas* sp., these pigments exhibit inhibitory effects against pathogenic bacteria, making them valuable in the development of novel antimicrobial agents. Furthermore, microbial pigments have demonstrated significant anticancer properties by inducing apoptosis and inhibiting the proliferation of cancer cells. They have also shown antioxidant activity, scavenging free radicals and protecting cells from oxidative damage. These findings suggest the potential use of microbial pigments in cancer therapy and as antioxidants in preventive medicine [5].

Food production

In the food industry, microbial pigments serve as natural colorants, replacing synthetic dyes with safer alternatives. Pigments derived from microorganisms such as *Monascus* spp., *Spirulina* spp., and *Serratia* spp, have been utilized to impart vibrant colours to various food products. Moreover, these pigments possess additional health benefits, including antioxidant and antimicrobial properties, thereby enhancing the nutritional value and shelf life of food products.

Textile manufacturing

Microbial pigments offer sustainable solutions in textile manufacturing, reducing the environmental impact associated with synthetic dyes. Pigments derived from microorganisms such as fungi, bacteria, and algae have been explored as eco-friendly alternatives for dyeing textiles. These natural pigments not only provide vivid colours but also exhibit excellent colour fastness and biodegradability, addressing concerns related to pollution and environmental sustainability [6].

Agriculture

In agriculture, microbial pigments have potential applications as bio-pesticides and bio-fertilizers. Pigments produced by microorganisms such as *Streptomyces* spp. and *Pseudomonas* spp. have shown insecticidal and nematicidal properties, offering environmentally friendly alternatives to chemical pesticides. Additionally, these pigments can enhance plant growth and productivity by promoting nutrient uptake and stimulating plant defence mechanisms.

Water science

Microbial pigments play a role in water science and technology, particularly in water purification and environmental monitoring. Pigments produced by microorganisms such as cyanobacteria and algae have been used as biosensors for detecting pollutants and assessing water quality. Furthermore, these pigments can facilitate the removal of contaminants through processes such as bioremediation and phytoremediation, contributing to the conservation of aquatic ecosystems. Finally, microbial pigments exhibit diverse applications in medicine, food production, textile manufacturing, agriculture, and water science. Their therapeutic potential, combined with their practical advantages such as eco-friendliness and sustainability, underscores their importance in various industries and research fields. Highlighting the detrimental effects of synthetic pigments, such as toxicological concerns and environmental pollution.

Research methodology

The research methodology employed in this study follows an exploratory approach, aiming to delve into the topic of microbial pigments and their applications. The study primarily relies on secondary data obtained from a variety of credible sources, including publications, the internet, articles, textbooks, and newspapers. This secondary data serves as the foundation for the research, providing valuable insights and information on microbial pigments.

The overall research design is descriptive in nature, focusing on providing an overview and analysis of the characteristics, trends, and applications of microbial pigments. Through descriptive research, the study aims to describe and analyse the various aspects of microbial pigments comprehensively. By utilizing secondary data from credible sources, the research ensures a thorough exploration of the topic, drawing from a diverse range of perspectives and sources.

DISCUSSION

Prospects and potential of microbial pigments

Microorganisms have long been utilized for the production of various compounds, ranging from vitamins to antibiotics, highlighting their versatility in biotechnological applications. The increasing popularity of natural substances in the food industry has led to a growing interest in colours and ingredients derived from biological sources, such as plants or microorganisms, which are considered natural. For instance, microbial colouring agents are already employed in the fish industry to enhance the pink hue of farmed salmon. Additionally, several natural colorants possess antioxidant properties, offering commercial potential in various industries.

Today, the sector can produce microbial pigments for use in textiles, food, cosmetics, and other applications. Microorganisms rich in colour and capable of producing pigments, including bacteria, yeasts, and fungi, are widely distributed in nature. Various pigments such as carotenoids, melanins, flavones, quinones, prodigiosins, as well as specific ones like monas citrine, violacein, or indigo, are synthesized by microorganisms.

Natural colorants and dyes derived from forests and wildlife are increasingly appealing to humans due to their non-toxic, biodegradable, and non-carcinogenic nature. The market value of synthetically manufactured pigments is declining as concerns over their safety and environmental impact continue to grow. Activism against artificial food colouring and substances gained international traction in the 1960s, leading to a shift towards the use of natural pigments and colorants promoted for their nutritional value (Figure 1).

Figure 1. Pigmented microorganisms at the surface of nutritive agar petri dish.

Market popularity and health benefits

Natural pigments have gained popularity in the market due to their potential health benefits, including pharmacological properties. They are widely utilized in various applications such as food production, paper manufacturing, textile dyeing, and agriculture. The preference for green technology emphasizes the use of less harmful and more natural materials in production processes [7].

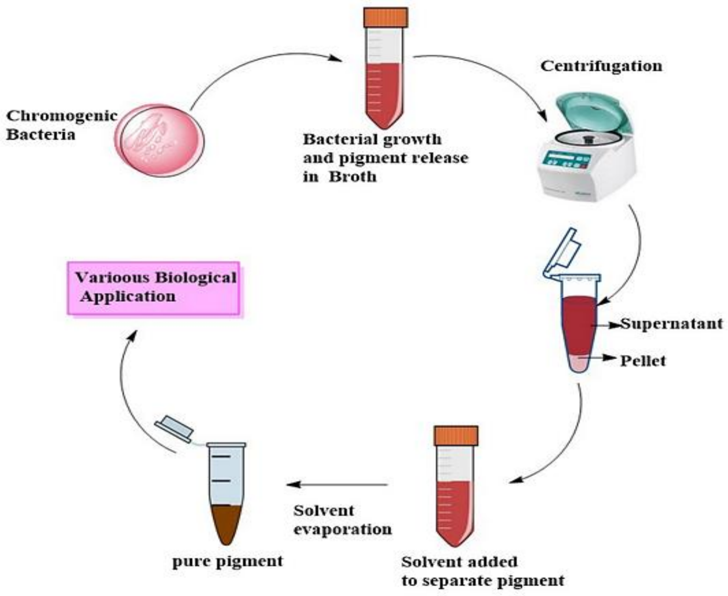
Banning of synthetic dyes

Several synthetic dyes and colorants have been banned from the market due to concerns over their carcinogenic precursor products and the environmental impact of their industrial waste disposal. This has further contributed to the rise in demand for natural alternatives.

High market value

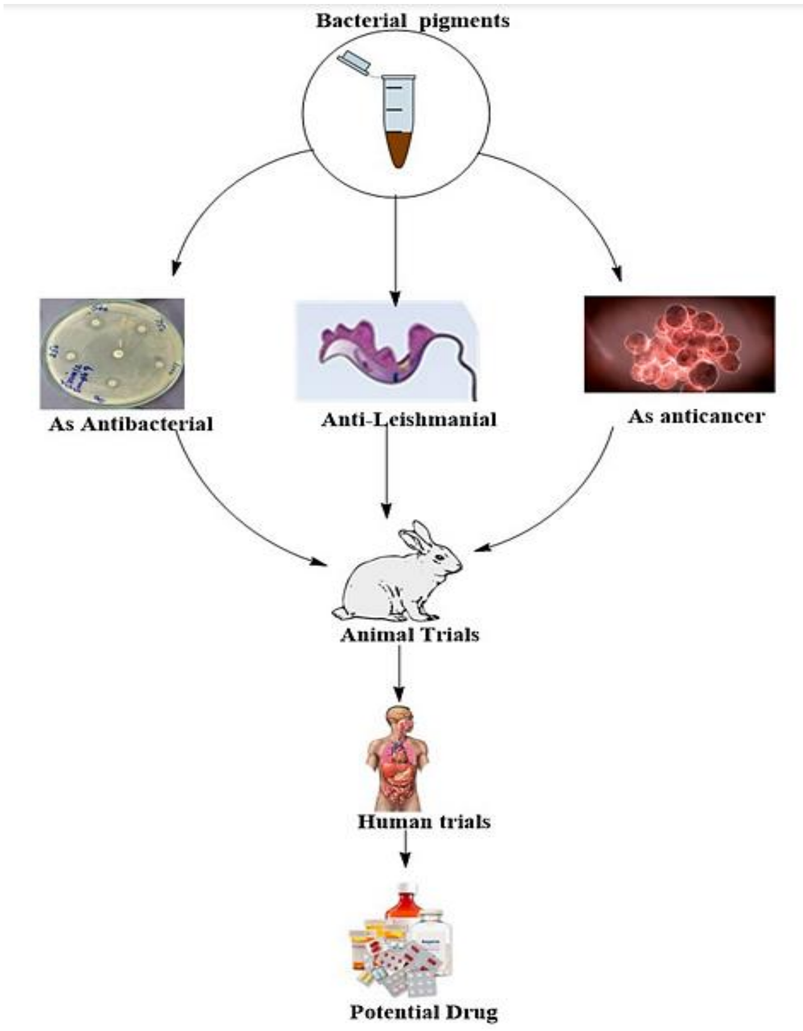
Natural pigments, colorants, and dyes hold a high market value due to their safety, biodegradability, and potential biological properties such as antioxidant and anticancer effects. Their widespread adoption signifies a shift towards more sustainable and environmentally friendly practices in various industries. Given the potential pharmacological properties of bacterial pigments, a thorough analysis of the diverse range of medicinal applications of these naturally occurring bacterial pigments was deemed required. For this reason, a large body of research was done to cover almost all of the advantages of bacterial pigments for health. The anticancer, anti-leishmanial, antibacterial, and antioxidant potential of bacterial pigments are only a few of the significant topics we cover in this review. Despite the pigments health benefits, there have also been discussions about their use in the food and textile industries. Figure 2 shows a schematic illustration of pigment extraction; the possible advantages are covered below.

Figure 2. Extraction of bacterial pigments.



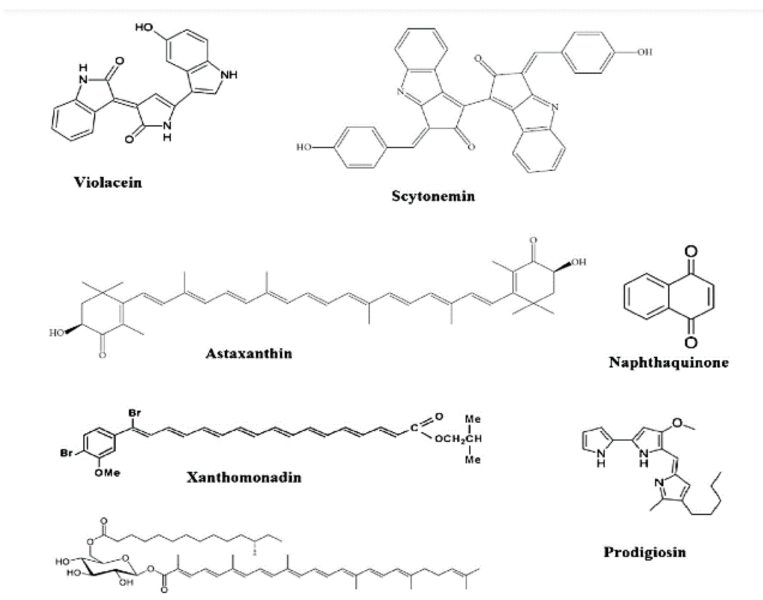
Activities related to bio-pharmacology have increasingly focused on compounds produced by microorganisms due to their pharmacological and physiological activity. Microbial pigments have garnered significant attention in this regard, with an expanding body of research investigating their antioxidant, anticancer, and antibacterial properties. As alternatives to synthetic substances, microbial pigments show promise in the development of new medications for addressing various pathological conditions in both the pharmaceutical and food sectors (Figure 3).

Figure 3. Applications of bacterial pigments in therapeutics.



This review addresses some of the major microbial pigments and their chemical structures, along with their medicinal importance (Figure 4).

Figure 4. Chemical structures of some pharmacologically active microbial pigments.



Antioxidant

Chronic illnesses such as diabetes, cancer, heart disease, and autoimmune diseases are often associated with oxidative stress caused by free radicals. Microbial pigments, including carotenoids, naphthoquinones, and vitexin, have demonstrated strong antioxidant activity due to their biological roles. Studies have shown that the bacterial pigment xanthomonad exhibits antioxidant potential by preventing photodynamic lipid peroxidation in liposomes and offering protection against photodamage. Additionally, the yellow pigment staphyloxanthin, derived from *Staphylococcus aureus*, has been found to protect against oxidative stress induced by carbon tetrachloride in Swiss albino mice. Further research has indicated that the microbial pigment naphthoquinone, produced from *Comamonas* testosterone, serves as a shield against free radicals such as superoxide. Moreover, violacein, another versatile microbial pigment, has demonstrated protection against oxidative damage in stomach ulceration by inducing the mucosal defense system.

Antimicrobial

Researchers are searching for more effective antimicrobial drugs as a result of medication resistance developing in human pathogenic bacteria. The advent of microorganisms with multidrug resistance has made treating infectious diseases more challenging in the modern world. A newer generation of antimicrobial agents must be developed in response to these evolutionary changes in harmful microbes. Consequently, it makes sense to look into natural antibacterial agents in order to address these issues. Researchers found that violacein inhibited the development of bacteria in addition to destroying them. Additionally, it is known that violacein has antiviral, antifungal, and antiprotozoal properties. When it comes to fighting human pathogenic bacteria including *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Salmonella typhi*, and *Vibrio cholera*, endophytic fungal pigment was found to be more effective than the commercial antibiotic streptomycin [8].

List of pigment-producing microorganisms and their proposed bioactivities

Here is a list of pigment-producing microorganisms along with their proposed bioactivities,

***Xanthomonas* spp.**: Antioxidant activity (xanthomonad pigment), potential antimicrobial properties.

Staphylococcus aureus: Antioxidant activity (staphyloxanthin pigment), potential protective effects against oxidative stress.

***Comamonas* testosterone**: Antioxidant activity (naphthoquinone pigment), potential protection against free radicals.

Violacein-producing microorganisms (e.g., *Chromobacterium* spp.): Antioxidant activity, potential protection against oxidative damage in stomach ulceration.

Pseudomonas aeruginosa: Production of pigments such as pyocyanin, which may have antioxidant and cytotoxic properties.

***Vibrio* spp.**: Production of pigments with potential antibacterial and antiviral properties.

***Aspergillus* spp.**: Production of fungal pigments with antioxidant and antimicrobial properties.

***Bacillus* spp.**: Production of pigments with potential antioxidant and antimicrobial properties.

Saccharomyces cerevisiae: Production of pigments with antioxidant properties, potential role in food and beverage applications.

Bioactivities

Production of pigments with potential antioxidant and antimicrobial properties. It's important to note that the bioactivities mentioned above are based on research findings and may vary depending on specific strains, environmental conditions, and extraction methods. Additionally, further studies are needed to fully understand and exploit the bioactive properties of pigment-producing microorganisms.

Classification of pigments

Microbes exhibit a diverse array of colour hues, including black, blue, bronze, brown, cream, grey, green, orange, purple, indigo, pink, red, yellow, metallic green, and rainbow colours. These pigments can be categorized into different groups based on their origin, spectrum, chemical composition, and visual characteristics.

Origin-based classification: Some pigments are derived from mobile genes, which can transfer between different organisms, leading to variations in pigment production.

Visual characteristics: Microbes, both prokaryotes and eukaryotes, exhibit monochromatic to polychromatic pigment combinations within the munsell colour system, which is based on their outward appearance. Certain higher organisms, such as hummingbirds and dragonfish, possess remarkable colour vision extending beyond the visible and near-infrared spectrums. However, humans are limited to detecting colours within the visible spectrum.

Phenomena represented by pigments

Natural pigments: Pigments derived from living organisms or natural sources.

Bioluminescence: Pigments that emit light through biochemical reactions.

Fluorescence: Pigments that absorb light at one wavelength and emit it at a longer wavelength.

Iridescence (structural colours): Colours produced by structural properties rather than pigments.

Non-spectral colours: Colours that cannot be represented by a single wavelength.

Types of pigments

Biological pigments: Derived from living organisms such as microorganisms, plants, and animals.

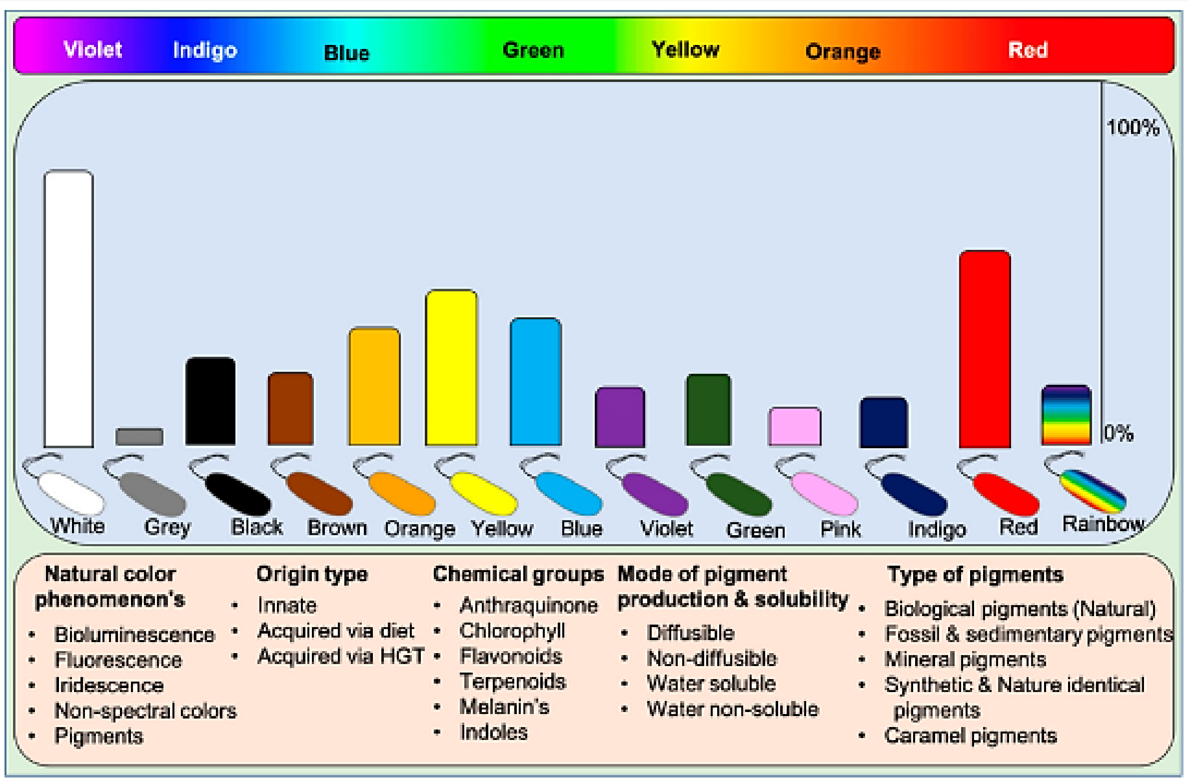
Fossil and sedimentary pigments: Biologically derived pigments preserved in fossils, providing evidence of evolution over millions of years.

Mineral pigments: Pigments derived from minerals found in nature.

Synthetic and natural pigments: Both artificially synthesized and naturally occurring pigments.

Caramel pigments: Pigments derived from caramelization processes, often used in food and beverage industries (Figure 5)

Figure 5. A wide array of pigmented microbes seen in nature. The abundance of the type of pigmented bacteria is depicted in bars based on the available literature. Rainbow bacteria are iridescent. Classification of pigments based on various aspects of biochromes. Chlorophyll pigments are not included in the data as they are ubiquitous.



Provide a comprehensive discussion of the reviewed literature, emphasizing the significance of microbial pigments in various fields. Explore the implications of the findings and potential areas for future research and innovation. Discuss the importance of sustainable alternatives to synthetic pigments and the role of microbial pigments in addressing this need.

CONCLUSION

Microbial pigments are involved in many aspects of ecosystem building, organism survival, and organism fitness. Microbial (fungi, bacteria, yeast, and microalgae) pigments are highly advantageous for a variety of uses in food, medicine, colorants, dyes, and imaging. The high manufacturing, high intensity, and low cost of synthetic colorants make them a popular alternative to the natural pigments derived from bacteria. Still, as synthetic pigments have been shown to have negative impacts on human health, demand for natural pigments is rising. To identify possible industrial uses, more studies on microbial pigments must be done. This review provides a quick overview of the evolutionary characteristics, the geographical significance of major pigments, biomedical uses, research gaps, and future directions.

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