

A DISTINCTIVE REVIEW UNVEILING ENDOPHYTIC MARINE MICROBE THROUGH THE PRISM OF PIGMENTS AND THEIR UNPARALLELED CONTRIBUTIONS IN MULTIFACETED INDUSTRIES

Amritha Suresh, Lavanya Jayaraman*, Subhashini Sivaji

Address(es):

Department of Biotechnology, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India – 603203.

*Corresponding author: lavanyaj@srmist.edu.in

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Review



ABSTRACT

The growing demand for sustainable and eco-friendly alternatives across industries has spurred interest in natural pigments, particularly those derived from marine endophytes. These microorganisms, which inhabit marine plants and algae without causing harm, have emerged as promising sources of bioactive compounds, including pigments like carotenoids, violacein, prodigiosin, and melanin with industrial relevance. This review aims to explore the potential of pigments derived from marine endophytes, highlighting their advantages over conventional synthetic and plant-based pigments. The primary objectives include evaluating the diversity of marine endophytes, the types of pigments they produce, their biological activities, and their applications in sectors such as food, cosmetics, textiles, and pharmaceuticals. To achieve these objectives, the review draws upon studies utilizing standard isolation methods like spread plate technique including surface sterilization of host tissues followed by culturing on nutrient media for the growth of endophytic strains. The isolated bacteria is identified preliminarily by morphological characterization and biochemical assays and confirmed by molecular techniques such as 16S rRNA sequencing. These methodologies ensure accurate taxonomic classification and assessment of pigment-producing capabilities. Marine endophytes offer several advantages: rapid growth, low-cost cultivation, and independence from seasonal variability, ensuring a stable pigment supply. Their pigments exhibit high solubility and stability, along with anti-oxidant, anti-microbial, and anti-inflammatory properties, further enhancing their industrial appeal. By summarizing current knowledge on marine endophyte-derived pigments, this review underscores their potential as sustainable alternatives to synthetic dyes and encourages further exploration into their commercial viability.

Keywords: Endophytes, Synthetic dyes, Natural pigments, Food colouring, Textile industry

INTRODUCTION

Pigment production and formulation play a major role in most of the sectors like food, textile, pharma, cosmetics, etc. The bright color produced gives a natural attractive look to the products manufactured. Therefore dyes and pigments are an essential one in the various sectors but the drawbacks include that the artificial synthetic dyes are harmful to the people using them (Mabuza *et al.*, 2023). The solution for this is the making and extraction of pigments and dyes from natural sources like from plant material, microbes and from some marine organisms. Among the developing field, the pigments isolated from the endophytic organisms play a vital role. Endophytic microbes are microorganisms, including bacteria, fungi, and actinomycetes, that colonize the internal tissues of living plants without causing any immediate, overt negative effects. They reside in the intercellular or intracellular spaces of plant tissues such as roots, stems, leaves, and seeds, forming a symbiotic relationship with their host plants. Endophytic microbes play a crucial role in plant ecology, agriculture, and biotechnology due to their diverse beneficial effects on host plants and their potential applications. Fungi are a heterotrophic category of organisms with diverse life cycles that form symbiotic partnerships with a wide range of autotrophic creatures (White *et al.*, 2019).

Both marine and terrestrial organisms contain endophytes in them they can adapt to any of the situation depending on the surrounding. Terrestrial endophytes are microorganisms, primarily fungi and bacteria, that live symbiotically within the tissues of plants without causing any harm. These microorganisms are found in various plant parts, including roots, stems, leaves, and seeds. They play a crucial role in enhancing plant growth, stress tolerance, and defense mechanisms against pathogens. Terrestrial endophytes contribute to plant health by producing bioactive compounds, such as enzymes, secondary metabolites, and phytohormones, which help in nutrient acquisition and protection from environmental stresses like drought or salinity. Additionally, many of these bioactive compounds have pharmaceutical, agricultural, and industrial applications, making endophytes a valuable resource for biotechnological research. The ability of terrestrial endophytes to establish mutualistic relationships with their host plants highlights their ecological significance and potential for sustainable solutions in agriculture and medicine (Peyrat *et al.*, 2019).

Endophytes have a symbiotic relationship between several plants and other organisms. Most of the endophytes are the bacterial endophytes where they reside

in roots, leaves and stem. Bacterial endophytes help host plants grow and become more resistant to diseases and environmental challenges. They can also control the formation of secondary metabolites with important therapeutic qualities and cause a variety of biological consequences. The secondary metabolites also includes a wide range of pigment production in which it helps in various mechanism of the microbes (Wu *et al.*, 2021).

Another type of endophyte found in plants are the fungal endophytes they live in the healthy tissues of the various plant parts. Endophytic fungi are mitosporic and meiosporic ascomycetes wherein they reside asymptotically in the internal tissues of the plant below the epidermal cell layer, colonizing healthy and living tissues through quiescent infections (Jia *et al.*, 2016).

The third type is the actinobacteria or the actinomycetes which is also a type of bacteria they are abundant in the soil environment and has majorly used in various sectors (Singh & Dubey *et al.*, 2018). They are gram-positive bacteria that are filamentous in nature. They are present both in terrestrial and in aquatic regions and play a crucial role in decomposing the dead materials. They also act as antimicrobials against the pathogens (Golinska *et al.*, 2015).

The endophytes have many advantageous properties and bioactive compounds which has antimicrobial activity, antioxidant activity, anticancer and much more. Apart from these, it also has the ability to produce pigments in certain environmental conditions. Not all the endophytes can produce pigments but some of the bacteria and fungi can produce pigments. These naturally producing pigments are used by various industries like food coloring, textile dyeing and pharma industries. The pigment producing endophytes are made to induce or produce pigments by culturing them *in vitro* in suitable medium for the extraction of the pigments. By extracting the pigments, it can be used as the effective alternate for the synthetic dyes which cause harmful effects.

To the fullest extent possible, a number of obstacles must be overcome in order to effectively utilize marine endophytes capacity for pigment production. These include the scalability of pigment synthesis, the isolation and cultivation of endophytes from marine environments, and the standardisation of extraction and purification procedures. Innovative biotechnology techniques and interdisciplinary cooperation are needed to meet these difficulties. On the other hand, the distinctive qualities of pigments obtained from marine sources offer a wealth of chances to develop high-quality goods that satisfy the expanding market for sustainable and natural substitutes.

The objectives and scope of this review gives the overall idea of marine endophytic organisms and the diversity of pigment produced by them, the industrial application of the endophytic pigments and the challenges faced by the industries.

MARINE ENDOPHYTES: AN UNTAPPED RESOURCE

Marine endophytes are microorganisms that play a crucial role as symbionts within their host organisms. As the term suggests, "endo" means "inside," and these microorganisms typically inhabit the intercellular and intracellular spaces of healthy marine plants, lichens, algae, seagrasses, soft corals, sponges, and other marine hosts, without causing harm. The presence and characteristics of these endophytes are influenced by various environmental factors, including pH, salinity, temperature, and the type of host organism. Notably, marine endophytes are also recognized for their medicinal properties, exhibiting significant antimicrobial and anticancer activities (Elkhateeb & Daba et al., 2022).

DIVERSITY AND TYPES OF MARINE ENDOPHYTES BACTERIAL ENDOPHYTE

Endophytic bacteria are symbiotic organisms that reside inside the host organisms and act as beneficial one. It does not cause any harmful effects to the host instead, it gains nutrients and provide protection to the host. Thus providing a symbiotic relationship with each other. The bacterial endophytes can live anywhere inside the tissues of leaves, roots, and stems of the plant or other host organism. Bacterial endophytes play a critical role in promoting plant growth through multiple mechanisms. They can fix atmospheric nitrogen, making it available to the plant, and produce phytohormones like auxins, gibberellins, and cytokinins that stimulate growth. Additionally, they enhance nutrient uptake by solubilizing phosphates and other essential minerals. Endophytic bacteria also protect plants from biotic stresses by producing antimicrobial compounds that suppress pathogens and inducing systemic resistance in plants. Under abiotic stresses like drought, salinity, or heavy metal toxicity, bacterial endophytes help plants adapt by producing stress-relief molecules, such as osmolytes and antioxidants. Beyond their agricultural importance, these bacteria produce bioactive metabolites with applications in medicine, such as antibiotics and anticancer agents, highlighting their potential for biotechnological exploitation (Megala & Vasan et al., 2023). Endophytes are beneficial microorganisms that can produce metabolites that are active similarly to the host plant, creating new opportunities for the growth and preservation of uncommon therapeutic plants (Adhikari & Pandey et al., 2021). These bacterial endophytes can be of any origin that some are of marine and some are terrestrial. Both serve as a beneficial organism to the host in which they reside.

FUNGAL ENDOPHYTES

Endophytic fungi are another promising source of organisms that has many advantages. These endophytic species have new and diverse secondary metabolites that can be used for various applications. With these secondary metabolites, they have the activity of anti-oxidant property, anti-inflammatory property, and antimicrobial property (Calado et al., 2021). Filamentous endophytic fungi can create a wide variety of biocolors, including as melanins, phenazines, flavins, carotenoids, quinones, violacein, indigo, monascins, rubropuntamine, rubropuntatin, and ankaflavin (de Melo Pereira et al., 2024).

ACTINOMYCETES

The order Actinomycetales of the phylum Actinobacteria includes both pathogenic and non-pathogenic gram-positive bacterium. They have high GC content and are a class of bacteria and most commonly present in soil but also sometimes in marine conditions. One of the most well-known genera of actinomycetes is *Streptomyces*, which has contributed significantly to the discovery of antibiotics such as streptomycin, tetracycline, and erythromycin. These organisms also produce antifungal, antiviral, anticancer, and immunosuppressive compounds, making them valuable for pharmaceutical research. Additionally, actinomycetes play a role in agricultural applications by producing biocontrol agents that protect plants from pathogens and promoting plant growth through nitrogen fixation and phosphate solubilisation (Singh & Dubey et al., 2018). They are mostly of fresh water and in some conditions, they both live in marine and fresh water. They have high moisture tolerance and live in moderate pH. They thrive in diverse habitats, often forming symbiotic relationships with plants and other organisms. The ability of actinomycetes to produce structurally diverse and biologically active molecules has made them a significant resource for drug discovery and environmental sustainability, highlighting their importance in both natural ecosystems and industrial applications. (Jagannathan et al., 2021).

HABITATS AND HOST ORGANISM

Plants often form associations with various organisms in their ecosystem to thrive, with microorganisms being among the most crucial. Beneficial bacteria, in particular, offer numerous advantages to their host plants, aiding in the tolerance of biotic and abiotic stresses that impede growth. These bacteria can reside

externally or internally within the plant. External bacteria, known as epiphytic bacteria, live on leaf surfaces, while rhizospheric bacteria inhabit plant roots in the soil. Conversely, endophytic bacteria live inside the plant. All these bacterial types share characteristics vital for promoting plant growth. Endophytic bacteria, a specialized subclass of rhizospheric bacteria known as plant growth-promoting rhizobacteria (PGPR), have evolved to invade their plant hosts. They possess traits beneficial to plant growth, often providing more significant advantages than many rhizospheric bacteria, especially under stress conditions (Afzal et al., 2019).

FACTORS INVOLVED IN DETERMINATION OF ENDOPHYTIC DIVERSITY

Different factors, such as the host plant species, environmental conditions, and isolation and identification procedures, determine the diversity of endophytes. In particular, the species of the host plant would matter, since different plants may support and harbour a rich pool of endophytes in unique niches and resources (Mushtaq et al., 2023). Besides climatic and altitudinal conditions, soil type, geographical location, and other environmental factors affect endophytic diversity by ensuring that the microbial populations connected to the plant also follow a specific pattern. Seasonal changes may influence abundance and composition of endophytes. Methodologies are also vital, including sampling methods, sterilization protocols, culture - dependent or independent techniques, which may all heavily influence the detected diversity. With the advent of next-generation sequencing (NGS) and 16S rRNA gene analyses, the resolution for identifying and classifying endophytic populations has been expanded and explored. Together, these factors shape richness, composition, and functionality, which makes the study of microbial diversity within plants quite complex (Vesterlund et al., 2011).

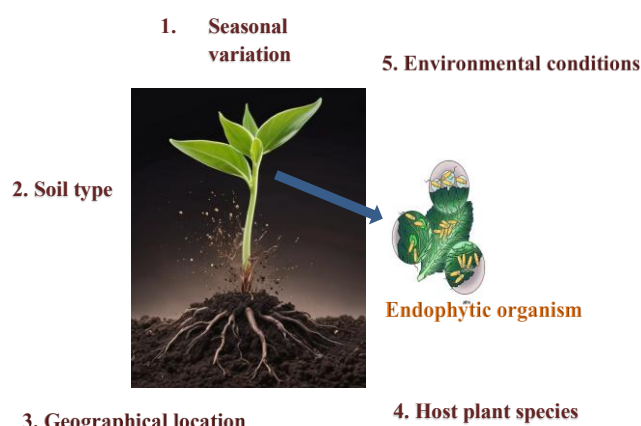


Figure 2 Factors affecting the diversity of the endophytic organism

TERRESTRIAL VS MARINE MICROBIAL PIGMENTS TERRESTRIAL MICROBES

The vast group of creatures known as terrestrial microorganisms, which includes bacteria, fungus, viruses, and protozoa, inhabit land habitats. They can be found in a variety of locations, such as deep terrestrial subsurface, farms, and woodlands (Beaver & Neufeld et al., 2024). Terrestrial microorganisms play a crucial role in ecosystems and offer numerous advantages that contribute to environmental health, agricultural productivity, and biotechnological applications.

Terrestrial microorganisms play a pivotal role in maintaining ecosystem functions through various mechanisms. In nutrient cycling, they act as essential decomposers, breaking down organic matter and recycling nutrients back into the soil, enriching fertility and supporting plant growth. Additionally, these microorganisms unlock vital nutrients such as nitrogen and phosphorus from organic compounds, making them readily available for plants, thereby reducing the dependence on chemical fertilizers. They also contribute significantly to carbon sequestration by converting organic matter into stable forms of carbon, aiding in soil carbon storage and mitigating climate change effects (Zhai et al., 2024).

In promoting plant growth, terrestrial microorganisms form symbiotic relationships with plants, such as mycorrhizal fungi, enhancing nutrient uptake and improving plant resilience against diseases and environmental stress. Some bacteria function as biofertilizers, promoting growth by increasing nutrient availability and enhancing soil structure. Microorganisms also play a vital role in bioremediation by degrading pollutants like heavy metals and organic toxins, restoring soil health and preventing environmental degradation (Peyrat et al., 2019).

Marine ecosystem is a vast area similar to the terrestrial ecosystem in which it contains variety of flora and fauna, in which both the plants and animals have endophytic organisms reside in them. Similar to the microbes present in land, marine microorganisms including fungi, algae and bacteria produce a wide range of pigments such as phycobilins, carotenoids and melanins. These pigments are often adapted to the unique conditions of marine environments, such as high

salinity and pressure. Marine pigments have demonstrated significant bioactivity, including antibacterial properties against pathogens like *Staphylococcus* and *Pseudomonas* species. This bioactivity is attributed to the unique metabolic pathways of marine microbes (Soliev et al., 2011). Some of the advantages of the marine microbial pigments is that the microbes have the high tolerance as they live in saline ecosystem. The marine microorganisms which are cultivated for pigment extraction include species

such as *Gracilaria* sp., *Kappaphycus alvarezii*, Suringar, *Sargassum fusiforme*, *Monostroma nitidum* Wittrock, *Saccharina japonica*, *Monascus* sp, *Undaria pinnatifida*, *Enteromorpha clathrate* (Muñoz-Miranda & Iñiguez-Moreno, 2023).

TYPES OF PIGMENTS PRODUCED BY MARINE ENDOPHYTES CAROTENOIDS

Carotenoids are natural pigments widely distributed in plants and microbes, including endophytic fungi and bacteria. These pigments are isoprenoid compounds distinguished by their long hydrocarbon chains with conjugated double bonds, which are responsible for their vivid colors. Carotenoids are broadly categorized into two groups: carotenes, which are hydrocarbons like β -carotene, and xanthophylls, which are oxygenated derivatives such as lutein and astaxanthin. In photosynthetic organisms, carotenoids play essential roles in light harvesting and photoprotection, safeguarding against photo-oxidative damage by quenching reactive oxygen species (ROS). They also act as antioxidants, neutralizing free radicals and protecting cellular components from oxidative stress. These properties make carotenoids valuable not only for the survival of the organisms that produce them but also for potential applications in human health (Hashimoto et al., 2016). In addition to their role in nature, carotenoids are widely used in various industries. In the food industry, they serve as natural colorants and nutritional supplements due to their association with health benefits, such as improving vision and reducing the risk of chronic diseases. In aquaculture, carotenoids like astaxanthin are used to enhance the pigmentation of fish and shellfish. They are also employed in the pharmaceutical and cosmetic industries for their antioxidant and anti-inflammatory properties. Recent advancements in biotechnology have enabled the sustainable production of carotenoids through microbial fermentation, making them a viable alternative to synthetic pigments and further expanding their commercial applications (Hagaggi & Abdul-Raouf et al., 2023).

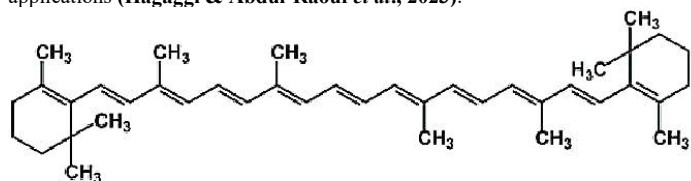


Figure 3 Structure of carotenoid

MELANIN

Animals, plants, and microorganisms all contain melanin, an insoluble, non-digestible pigment with a complex molecular structure that ranges in color from dark brown to black. Melanin is produced through the polymerization of indolic and phenolic chemicals. Melanin is a complex biological material with a wide range of biological functions, such as anti-inflammatory, antiviral, antibacterial, thermoregulatory, antioxidant, and chemo protective effects (Suwannarach, Kumla, Nishizaki, et al., 2019). Melanin is found in many eukaryotic creatures and has a number of purposes, including shielding human skin from UV rays, influencing disease virulence, and influencing insect development and physiology (Gaber et al., 2020). This melanin are produced by the endophytic organisms naturally and also can be made to produce by inducing it to various parameters and can be used in various industries.

Although melanin helps protect the organism from harmful UV and oxidative stress, it presents a disadvantage in certain contexts. Its primary demerit lies in its likely relationship with discolored skin pigmentation, a condition commonly known as hyperpigmentation or melasma, produced by an overproduction of melanin stimulated through hormonal changes, sun exposure, or inflammation. Unequal pigmentation has cosmetic and causes aesthetic concern and leads to loss of self-confidence. In medical terms, excess melanin deposited in tissues leads to discoloration and tissue damage, such as in the case of ochronosis. Melanin also has a tendency to bind metals and other molecules, and sometimes this may lead to an accumulation of toxins within the molecule that could affect cellular function. In industries, the high stability of melanin can be challenging to remove or modify, especially in cosmetic formulations to lighten skin tones. Moreover, melanin production by microbial contaminants contributes to biofouling, which is a problem to control in some environments.

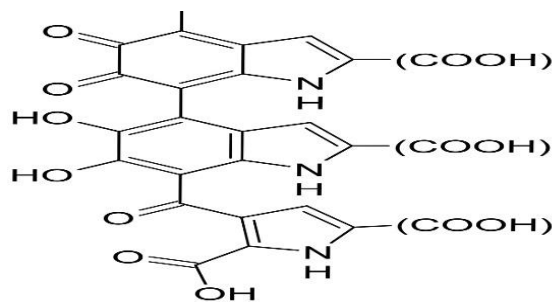


Figure 4 Structure of Melanin

VIOLACEIN

Violacein is a purple pigment primarily produced by marine and terrestrial bacteria. It is one of the well-known bioactive pigments that have high potency in inhibiting tumor formation, antibacterial, antifungal, and antiviral activities. All these therapeutic properties of violacein make it an important compound in the pharmaceutical industry. Violacein shows cytotoxic effects against many different cancer cell lines, thus providing it as an ideal candidate for anticancer drug development. Its antibacterial action is also potent against both Gram-positive and Gram-negative bacteria, thus further establishing its potential in fighting drug-resistant pathogens. Violacein is mainly purified from bacteria species, including *Pseudoalteromonas* sp., *Chromobacterium violaceum*, *Janthinobacterium lividum*, *Duganella violaceinigra*, *Collimonas*, and *Iodobacter*. Among all the above-described bacteria, however, *Chromobacterium violaceum* is so far the organism that has extensively been studied about the production of violacein. The compound is synthesized during the shikimate pathway but by specific enzymes (Velmurugan et al., 2020) (Pauer et al., 2018). Despite the many advantages violacein possesses, it also has some disadvantages. One of its disadvantages is its potential influence on gut microbiota. It can cause microbial imbalance in the gut, leading to inflammatory, allergic, or metabolic diseases. This makes the dosage and application of violacein very careful.

Other than its pharmacological properties, violacein is under study as a potential biosensing and dye material due to its unusual color and stability. More research and optimization are carried out in improving the production via microbial fermentation or genetic engineering so that it would become a feasible, efficient substitute for synthetic chemical dyes (Kanade et al., 2022).

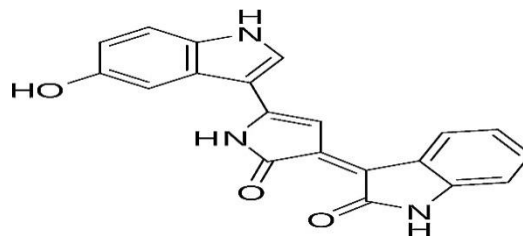


Figure 5 Structure of Violacein

PYOCYANIN

P. aeruginosa produces the potent bacterial pigment pyocyanin, which is antifungal since it can inhibit the fungal electron transport chain (DeBritto et al., 2020). It act as antimicrobial agent, food preservative and as antifungal agent (Mudaliar & Bharath Prasad et al., 2024). These pigment are of blue green color because of production of two secondary metabolites: pyocyanin (blue) and pyoverdine (green). Pyocyanin: An abundant blue-green phenazine pigment that dissolves in water. It may be used as a textile dye and has antibacterial properties. Pyoverdine A green-producing bioluminescent siderophore. It fluorescence under ultraviolet light (El-Fouly et al., 2015) .

ANTHOCYANIN

Anthocyanins are water-soluble pigments primarily responsible for the red, blue, and purple colors in plants. These compounds are also produced by certain microorganisms, including fungi, bacteria, and yeast. Microbial production of anthocyanins has gained attention due to its potential for sustainable production methods. Unlike plant-based extraction, which can be resource-intensive, microorganisms can be engineered to synthesize these pigments in controlled environments. This microbial production process is seen as a promising alternative for applications in the food, cosmetic, and pharmaceutical industries, providing a natural source of colorants that can be produced efficiently and in large quantities (Khoo et al., 2017).

PRODIGIOSIN

Prodigiosin is a bright red-pink pigment produced by various microorganisms, primarily *Serratia marcescens*, but also by species of *Pseudomonas*, *Vibrio*, and *Hahella*. It belongs to the family of tripyrrole pigments and is known for its striking color and bioactive properties. Prodigiosin is a secondary metabolite synthesized through a complex biosynthetic pathway involving multiple enzymes. This pigment has garnered significant interest due to its diverse biological activities. It exhibits potent antibacterial and antifungal properties, making it effective against a wide range of pathogens. Additionally, prodigiosin has shown promising anticancer activity by inducing apoptosis in cancer cells without harming normal cells. It also possesses immunosuppressive, antioxidant, and anti-inflammatory properties, making it a valuable compound for pharmaceutical research. Prodigiosin's applications extend beyond medicine. It is explored as a natural dye in the textile and food industries due to its stability and vibrant color. Moreover, its eco-friendly production through microbial fermentation offers a sustainable alternative to synthetic pigments. However, the commercial use of prodigiosin faces challenges, such as optimization of large-scale production and concerns about its toxicity at higher concentrations. Ongoing research aims to overcome these limitations and unlock its full potential for industrial and therapeutic applications (Srilekha et al., 2024).

OTHER PIGMENTS

There are several other important pigments found in nature, each with unique properties and functions. For example, *carotenoids* are a class of pigments responsible for yellow, orange, and red colors in plants, algae, and some

microorganisms. These pigments are vital for photosynthesis and are also antioxidants, providing health benefits when consumed. *Chlorophylls*, which are green pigments, are essential for photosynthesis in plants and algae (Saubenova et al., 2024). They help in capturing light energy, which is crucial for converting carbon dioxide and water into glucose and oxygen. *Bilirubin* is a yellow pigment produced during the breakdown of red blood cells in animals. It plays a role in the metabolism of heme and is excreted in bile. *Phycocyanin* and *phycoerythrin* are pigments found in red and blue-green algae, respectively. These pigments assist in photosynthesis by absorbing light in the blue to green range, expanding the spectrum of light available for the process (Ahmadi et al., 2024). *Melanin* is a pigment found in animals, fungi, and bacteria, providing protection from ultraviolet (UV) radiation. In humans, it contributes to skin, hair, and eye color and serves as a natural defense mechanism against UV-induced damage. Each of these pigments has significant biological roles and potential applications in various industries, from medicine to food coloring. Apart from the pigments of melanin and carotenoids there are some other pigments, which are isolated and not yet known, and to be identified some of them are the pink coloured, orange brown, violet etc.

OPTIMIZATION OF PIGMENT PRODUCTION

The pigments produced by the microbes like bacteria, fungi are very less in quantity, and the need of the pigments by the industries is high. To reach the desired quantity the pigments from the bacteria is optimized to different conditions like various temperature, pH, salinity, various media composition etc.

Table 1 Pigment optimization conditions

Sl.No.	Name	Organism	Pigment colour	Optimization parameter	Reference
1.	<i>Enterobacter</i> sp. PWN1	Bacteria	Pink	Temperature, pH, inoculum percentage	(Poddar et al., 2021)
2.	<i>Pezizula</i> sp. BDF9/1	Bacteria	Red	Incubation time, temperature and carbon, nitrogen, phosphate, and metal ion source.	(Banerjee et al., 2016)
3.	<i>Aspergillus</i> Sp. N11	Fungi	Orange brown	Temperature, pH, media composition	(Ashfaq et al., 2022)
4.	<i>H. investiens</i>	Fungi		Culture media, pH values, shaking rates, temperature, incubation rate.	(de Melo Pereira et al., 2024)
5.	<i>Nigrospora aurantiaca</i> CMU-ZY2045	Fungi	Red	Carbon and nitrogen source, temperature, cultivation period, culture medium.	(Suwannarach, Kumla, Nishizaki, et al., 2019)
6.	<i>Spissiomycetes endophytica</i>	Fungi	brown-black	Culture media, pH, temperature.	(Suwannarach, Kumla, Nishizaki, et al., 2019)

PATHWAYS TO IMPROVE PIGMENT PRODUCTION

Optimizing fermentation conditions is critical for enhancing pigment production in microbial systems. One key aspect involves fine-tuning nutrient management, particularly the selection and concentration of carbon and nitrogen sources. For example, studies have demonstrated that glucose and yeast extract significantly boost pigment yield in certain bacterial strains. Additionally, physical parameters such as pH, temperature, agitation speed, and salt concentration have a profound impact on microbial growth and pigment synthesis. Many pigment-producing bacteria exhibit optimal activity at temperatures ranging between 30°C and 37°C and at neutral pH levels. Agitation and aeration are equally important, as they enhance oxygen transfer and ensure uniform nutrient distribution. Research has shown that increasing agitation speeds can further stimulate pigment production in specific microbial strains by supporting their metabolic processes more effectively (Meeraj Fatima and K. Anuradha., 2022).

Biotechnological advancements have opened new avenues for improving pigment production in microbial systems. Genetic engineering plays a crucial role by enabling the cloning of genes involved in pigment biosynthesis, thereby enhancing production levels. This technique allows researchers to modify and optimize metabolic pathways for increased efficiency in pigment synthesis. Similarly, metabolic engineering involves the targeted alteration of these pathways through gene editing or synthetic biology methods, redirecting cellular resources to boost pigment yield. Additionally, the integration of synthetic biology with conventional fermentation processes has facilitated the development of microbial strains with optimized metabolic frameworks, further improving pigment production efficiency (Venil et al., 2020).

Advanced cultivation techniques have greatly improved microbial pigment production by offering better control and efficiency. Submerged fermentation, for example, has proven to outperform solid-state fermentation due to its ability to maintain precise environmental conditions, which significantly boosts pigment yields. Additionally, cell immobilization techniques have emerged as a promising approach, as they enhance pigment synthesis by enabling repeated batch

processing and providing greater cell stability throughout the fermentation process (Venkatachalam et al., 2024).

Innovative extraction methods play a critical role in improving the efficiency and cost-effectiveness of pigment recovery from microbial biomass. Optimizing solvent extraction techniques, such as solvent-solvent extraction or the use of supercritical fluids, can significantly enhance pigment yield while reducing overall costs. Additionally, advanced approaches like micro and nano-encapsulation have been developed to encapsulate pigments in microscopic or nanoscale carriers. This not only improves the pigments' stability and solubility but also enhances their performance in various applications, particularly in the food industry (Venil et al., 2020).

Co-pigmentation strategies involve blending different pigments to enhance their colour stability and intensity, making them more effective and visually appealing. This approach is particularly beneficial for improving the quality of pigments obtained from microorganisms, ensuring they meet the desired standards for use in food and cosmetic applications.

ADVANTAGES OF USING NATURAL PIGMENTS FROM ENDOPHYTES OVER SYNTHETIC DYES

Synthetic dyes

The synthetic dyes used in textile production are difficult to eliminate from wastewater because they are made to withstand ordinary oxidation and reduction processes. Conversely, oxidants and reductants are not required for the biodegradation of natural colours. In contrast to natural dye degradation, which can totally breakdown in the presence of natural conditions, the decomposition of synthetic colors yields by products that are known to be toxic. The complicated molecular structures and synthetic origins of synthetic dyes reduce the biodegradability of their effluents, making them dangerous to the environment and water streams. Being mostly non-biodegradable, synthetic colors cause ecological issues by building up in rivers and on land (Affat et al., 2021). To overcome these hurdles natural colouring will give a better way to the artificial dyeing.

These man-made colorants of synthetic dyes are produced using various chemical compounds and are most widely used by industries such as textiles, food, cosmetics, and pharmaceuticals. They prefer synthetic dyes for their color intensity, the cost-effectiveness, and its stability. Complex chemical processes derived from petroleum, coal tar, and other precursors are followed to synthesize these dyes. The general types of synthetic dyes may be classified by their chemical structure or application. Azo dyes form the largest class of dyes. They consist of one or more azo groups: (-N=N-). This group, especially in conjunction with other functions like sulfonamide, azo dyes include such highly colorful compounds like methyl orange, red Congo. Their use covers an enormous share in textiles, leather, paper industry (Benkhaya et al., 2020). The basis of anthraquinone dyes are represented by anthraquinone and produce different shades of blue, violet and green. They are extensively used in the production of synthetic indigo, a key dye in denim manufacturing. Triphenylmethane dyes, including malachite green and crystal violet, are bright and vibrant, used in paper, textiles, and microbiological staining. Reactive dyes, such as Procion dyes, form covalent bonds with fibers like cotton, making them highly durable. These are commonly used in textile printing and dyeing. Synthetic fibers like polyester use dispersed dyes. Due to the minute, nonionic size of its molecule, this synthetic dye attaches onto hydrophobic fabrics. However, aside from textiles, this synthetic dye can also be seen in food and beverages. This yellow synthetic dye, known as Tartrazine, is common in processed food (López-Gutiérrez et al., 2013). Another food coloring synthetic dye is Allura Red AC used in beverages, candies, and desserts. While very functional, a few food dyes have created health concerns regarding possible allergic reaction or toxicity. Research and medicine also utilize synthetic dyes. Among these are the fluorescent dyes like rhodamine and fluorescein used for labelling and imaging in biological studies. Methylene blue is an example of synthetic dyes that can be used as an antiseptic and in staining diagnostic procedures. Although synthetic dyes have drastically transformed industries, they also play a large role in environmental factors. Their production and disposal often release toxic chemicals into ecosystems, leading to water pollution and health hazards. Consequently, there is a growing interest in developing eco-friendly synthetic dyes and promoting sustainable dyeing technologies to minimize these adverse effects.

Natural pigments

Natural pigments apart from giving natural colours they are nontoxic, and are not harmful to the environment. They also have medicinal properties anti-inflammatory property, antioxidant and anticancer property (Numan et al., 2018). Plants and microorganism that include microalgae, fungi, and bacteria produce these pigments. These pigments have various applications in multiple industries like food, textile, pharma, cosmetics, and other related industries where they use colouring and dyeing (Paillié-Jiménez et al., 2020).

Natural pigments are valuable compounds extracted from microorganisms and plants and are used in food, pharmaceuticals, cosmetics, and textiles. These pigments are of great interest because they are biodegradable, low in toxicity, and potentially beneficial to health. Microorganisms, including bacteria, fungi, and algae, are significant sources of natural pigments. Bacterial pigments, such as prodigiosin, pyocyanin, and violacein, have been shown to possess antibacterial, antioxidant, and anticancer properties. Actinomycetes, specifically Streptomyces species, produce melanin and carotenoids pigments used in medicine and cosmetics. Fungi, especially Monascus and Aspergillus species, produce monascin and flavins pigments used extensively as food colorants. Algae, specifically cyanobacteria and microalgae, produce chlorophyll, phycocyanin, and phycoerythrin pigments that are used as natural dyes and in health supplements. Plants are another storehouse of such natural pigments, responsible for the colors observed in fruits and vegetables, as well as those of flowers, leaves, and so many more. Main plant pigments include anthocyanins, carotenoids, chlorophylls, and betalains. Anthocyanins, causing red, blue, and purplish red colors, are ubiquitous in berries and grapes and much prized for its antioxidant activity in eggplants (Phan et al., 2020). Carotenoids range from yellow to orange and red colors, which can be found in carrots, tomatoes, and bell peppers, and have health benefits such as enhancing vision and improving immunity. Chlorophyll, the most important pigment of green color to cultivate life through photosynthesis, is being utilized as organic supplements and cosmetics. Betalains of beets and amaranth contribute to their antioxidant and anti-inflammatory activity. Both microbial and plant-derived pigments are increasingly being used as natural alternatives to synthetic colorants. They provide additional functional benefits, including bioactivity and environmental sustainability, which makes them highly desirable for applications in modern industries (Di Salvo et al., 2023).

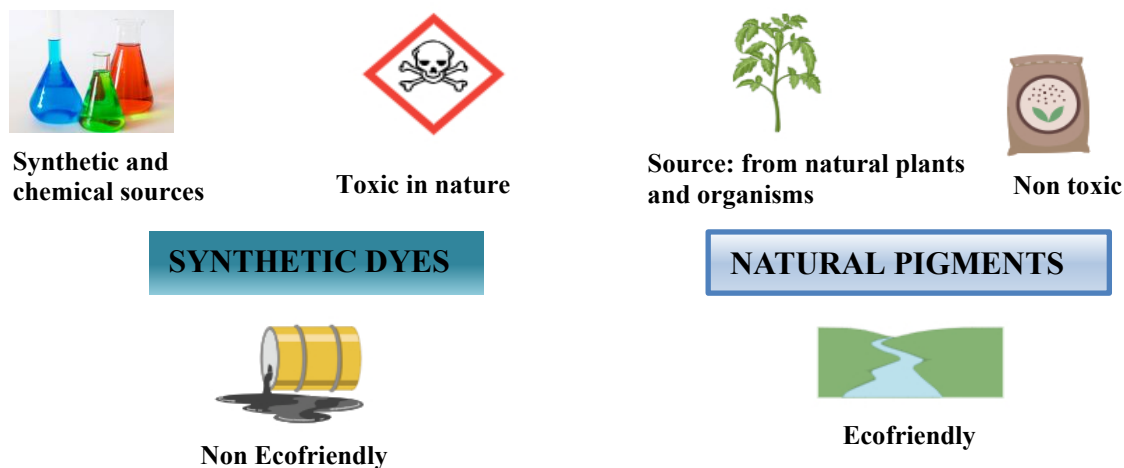


Figure 6 Synthetic vs Natural pigments the overall view on the ecosystem

Challenges in Research and commercialization of the bio-pigments isolated from microorganisms

LOW YIELD CHALLENGES IN PIGMENT PRODUCTION

The most important limitation of using microbial strains for pigment production is the inherent low yield. Many natural strains produce pigments in such minimal amounts that scaling up to commercial levels becomes highly problematic. The large-scale production of these pigments often turns out to be economically nonviable due to the costs of cultivation and extraction exceeding the benefits. To overcome this, advanced strain improvement techniques are used, including mutagenesis, where genetic variations are induced to enhance pigment biosynthesis, and metabolic engineering, which involves modifying specific metabolic pathways to increase pigment production. However, these methods are both time-intensive and complex, requiring detailed genetic and metabolic understanding of the microorganism. Additionally, strain improvement may lead to unexpected changes in other cellular processes, necessitating further optimization to maintain overall strain viability and productivity (Sen et al., 2019).

CHALLENGES IN OPTIMIZING FERMENTATION CONDITIONS

The production of pigments by microbial strains is very sensitive to fermentation conditions, such as temperature, pH, oxygen levels, and nutrient availability. Optimization of these factors is crucial for maximizing pigment yields. However, the optimal balance is often difficult to find, as different strains and even different stages of growth require specific conditions. The process often involves extensive research, experimentation, and trial-and-error to identify the best fermentation parameters. Moreover, the industrial-scale maintenance of these conditions creates additional complexity due to the susceptibility of slight variations in yield and quality of pigment. Advanced bioreactor systems, process control technologies, and predictive modeling are being increasingly used to overcome these challenges, but implementation is resource-intensive, requiring high investment in infrastructure and expertise (Sen et al., 2019).

Expensive extraction processes: Extracting microbial pigments often requires expensive and time-consuming methods. Organic solvents, which are usually applied at an extraction step, multiply the production costs and may not be compatible with the natural product profile that needs to be attained before obtaining regulatory approval. Moreover, the solvent recovery and disposal

methods are added to the cost of operation. Other green extraction techniques are supercritical fluid extraction or aqueous two-phase systems, although these need further optimization and investment (Sen et al., 2019).

Instability Problems: The microbial pigments are normally unstable towards light, heat, and oxygen when exposed, thus degrading the color strength and causing instability. These problems arise concerning storage and shelf life, particularly for food and cosmetics applications. Highly advanced stabilization methods involving microencapsulation and non-ionic adsorption resins have been introduced in order to safeguard the pigment against environmental degradation. However, this makes production much more complicated and costly (Rajendran et al., 2023).

Regulatory Approvals Process: All novel natural colourants, including those intended to be used for food and cosmetic application, are supposed to undergo the most rigorous and extensive safety tests. These consist of toxicity assessments and allergenicity testing and follow international standards. These lengthy processes as well as costing much often acts as a dampener to any investment in new microbial pigments, especially amongst startups or other relatively smaller organizations (Rather et al., 2023).

Toxicity Issue: Some pigmented microbial strains may also produce toxic secondary metabolites, like mycotoxins, which restrict their use as food colorants. Screening and selecting non-toxic strains or modifying existing strains through metabolic engineering are crucial but require more resources and expertise. Validation of strains should be proper to ensure safety for consumers (Tuli et al., 2015).

Competition with Synthetic Dyes: Despite this, synthetic dyes will still hold sway due to lower prices, durability, and an immense array of colours. However, since the pigments used in these synthetic dyes pose greater danger both to health and the environment and have higher costs than the former ones, their preference would need incentives and/or reduction strategies for its price in comparison with natural ones (Tuli et al., 2015).

Scalability: The scale-up of pigment production from laboratory to industrial scale poses significant logistical challenges. High-density cell culture techniques, cell immobilization, and advanced bioreactor systems may improve the efficiency of production. However, these approaches demand significant technological investment, process optimization, and infrastructure development, making them less accessible to smaller players (Sen et al., 2019). Transitioning pigment production from laboratory-scale to industrial-scale presents significant logistical challenges. High-density cell culture techniques, cell immobilization, and advanced bioreactor systems may improve production efficiency. However, these approaches demand substantial technological investment, process optimization, and infrastructure development, making them less accessible to smaller players.

Stability Issues: Microbial pigments are typically prone to instability from environmental conditions including light, heat, and exposure to oxygen which break them down, resulting in reduced color strength. Such instability causes difficulty in storing or having shelf lives in areas of food and cosmetics, for example. Techniques developed on the advancement in stabilization methods that involve microencapsulation and non-ionic adsorption resins will safeguard pigments against environmental degradation; however, the processes complicate and are cost-intensive during production (Sen et al., 2019).

Regulatory Approval Processes: For any newly identified natural colorant, especially intended for use in food and cosmetics, extensive safety evaluations are demanded before the colorant receives approval for commercial applications. These assessments may include toxicity studies, allergenicity testing, and international standard compliance. As a result, lengthy and costly regulatory procedures often deter investments in the development and marketing of microbial pigments, mainly for startups or smaller enterprises (N. Sharma et al., 2024).

Consumer Preferences: Despite increased consumer demand for natural products, a significant gap persists in the area of awareness and acceptance of microbial pigments compared with plant-based dyes. These negative perceptions limit the adoption potential in the marketplace. Educating consumers on sustainability, safety, and health aspects associated with microbial pigments will help fill the gap toward expanded acceptance and utilization.

Competition from Synthetic Dyes: The market continues to be dominated by synthetic dyes because of their low cost, stability, and vibrant color options. Natural pigments are safer and more environmentally friendly, but their higher cost and susceptibility to environmental degradation make them less competitive. Bridging this gap requires either cost-reduction strategies or incentives to prioritize natural over synthetic options.

Integration of New Technologies: Recent developments in synthetic biology and metabolic engineering hold much promise for increasing pigment production.

These technologies can be used to optimize metabolic pathways, increase yield, and reduce costs. However, they are difficult to integrate into existing systems and require specialized expertise, costly equipment, and regulatory approval for genetically modified strains. The sustainability of microbial pigment production hinges on addressing these challenges while maintaining economic feasibility. Efforts to develop scalable, low-cost, and environmentally friendly methods will be pivotal in making microbial pigments a viable alternative to synthetic dyes in diverse industries.

INDUSTRIAL APPLICATIONS OF MARINE ENDOPHYTE PIGMENTS TEXTILE INDUSTRY

The textile industry has been a cornerstone of human civilization, becoming increasingly significant as contemporary society places greater value on aesthetics. However, it is also the second most polluting industry globally, with substantial environmental impacts arising from fabric production and dyeing processes (Simsek Geyik et al., 2024). Dyes, categorized as natural or synthetic based on their origin, have been used since prehistoric times. Natural pigments, derived from plants, animals, and microorganisms, have historically coloured human life, evident in clothes, food, and furniture. These pigments not only add colour but also play crucial roles in the natural world, such as camouflage, warning signals, and attraction. The study of colour spans various fields including science, art, and philosophy, highlighting its profound influence on human instincts and behaviours. Metabolic processes in living organisms produce natural pigments like carotenoids and anthocyanin, with synthetic equivalents like beta carotene and canthaxanthin mimicking these natural hues (Mani et al., 2024). Apart from the plants and animals endophytic organisms of fungi and bacteria play a vital role in pigment production where in the place of toxic dyes used in the textile it is a good source of replacement of natural colorant (Suwannarach, Kumla, Watanabe, et al., 2019). Researchers discovered two bacterial strains, NP2 and NP4, capable of producing intense blue and red pigments. These pigments were used directly for fabric dyeing without any purification steps. Studies confirmed that the pigments are part of the prodigiosin family, which is known for its coloring abilities. The pigments showed strong affinity for synthetic materials like polyamide and acrylic, produced moderate shades on polyester and triacetate, and only lightly stained natural fibers such as cotton. (Kramar et al., 2014).

FOOD INDUSTRY

Food industries is another major sector that uses the colouring agents for the aesthetic and its attractive view. People love food when it is more attractive and colourful and therefore it needs colour. Food colouring with artificial colours or synthetic dyes may cause adverse effects on health conditions on humans and other diseases related problems may occur. In order to avoid these things natural colouring are used in the food products. Natural pigments have potential as food additives; with red being, the most commonly used color to attract consumers. Beta-carotene is becoming increasingly important in the food industry as a colorant (Di Salvo et al., 2023). Some of the studies have made the jelly's and hard boiled candies with the bright coloured pigments obtained from the bacteria. The stability and the consistency of the products are tested and they are used and commercialised (Sharma & Ghoshal et al., 2021).

PHARMA INDUSTRY

The next to food industry is the pharmaceuticals and the microbial pigments are favoured over plant pigments due to their rapid growth cycles using inexpensive culture mediums, consistent availability regardless of weather conditions, ease of processing, and high stability and solubility. Microbial pigments have promising applications in the pharmaceutical industry due to their bioactive properties. Many of these pigments, such as prodigiosin, violacein, and carotenoids, exhibit antimicrobial, anticancer, antioxidant, and anti-inflammatory activities. For instance, prodigiosin has shown potential as an anticancer agent by inducing apoptosis in cancer cells. Violacein, derived from certain bacteria, demonstrates antimicrobial and antitumor properties, making it valuable in drug development. Additionally, microbial carotenoids, known for their antioxidant effects, are explored for use in preventing oxidative stress-related diseases. These pigments, produced sustainably through microbial fermentation, offer a natural and cost-effective alternative for developing novel therapeutic agents. (Ashfaq et al., 2022).

ANTIBACTERIAL PROPERTY

The various natural pigments isolated from the marine organisms has shown antibacterial activity against many bacterial species. It inhibits the growth of the bacteria in which it causes any diseases (Navaz et al., 2021). The assays like MIC and MBC determine the concentration and the antibacterial property of the pigments (Ababutain et al., 2021). Most of the pigments of red, orange and brown pigments show antibacterial effect against the common bacteria like *Staphylococcus aureus*, *E. coli* and *Pseudomonas* (Yanti et al., 2021).

Cell Membrane Disruption: Certain pigments can compromise the structure of bacterial cell membranes, causing them to lose integrity and eventually leading to

cell lysis. For example, carotenoids have been reported to alter bacterial membrane permeability. Reactive Oxygen Species (ROS) Production: Pigments like pyocyanin can generate ROS, which create oxidative stress and damage vital cellular components in bacteria. This mechanism is particularly effective against Gram-positive bacteria due to their less complex cell wall structure.

Enzyme Activity Inhibition: Some pigments can block the activity of key enzymes required for bacterial metabolism, thereby hindering their growth. Prodigiosin, for instance, has been found to disrupt bacterial respiration processes. Researchers explored the potential of bacterial pigments for industrial use by collecting soil samples from different regions in Karnataka. From these, 25 actinomycete strains were isolated, and one strain, named *Streptomyces sp.* BJZ10, showed high pigment production. The pigment extract, known as CFDP, demonstrated significant antibacterial activity against *Staphylococcus aureus*, MRSA, and *Vibrio cholerae*, as well as anticancer effects on HeLa cells. It also showed strong antioxidant activity and was non-toxic to normal human cell lines, making it a promising candidate for commercial use (Kazi et al., 2022).

ANTICANCER PROPERTY

Several studies have been made for the assessment of the anticancer property of the pigments isolated from various endophytic organisms. Some of the cell lines used for the study are SK-MEL-2, human breast cancer cell line (MCF-7) and HeLa cells (Nawaz et al., 2021). The anticancer property can be evaluated by MTS assay where with the change in colour the cell viability is calculated (Sebola et al., 2020). Researchers identified strain CPE04, showing strong extracellular red pigment production. The pigment extract, known as CFDP, demonstrated significant antibacterial activity against *Staphylococcus aureus*, MRSA, and *Vibrio cholerae*, as well as anticancer effects on HeLa cells. It also showed strong antioxidant activity and was non-toxic to normal human cell lines, making it a promising candidate for commercial use (Mishra et al., 2021).

COSMETIC INDUSTRY

Cosmetics is the other major sector in which most of the colour are used for their aesthetic and attractive view. The bright colours attract people in buying items. These colouring agents used in the cosmetic items are mostly of synthetic dyes as these dyes as said before can cause many side effects and toxic to humans. Instead of these natural pigments play a vital role as the pigments obtained from plants and various microbes can be used in the cosmetic products. As these various pigment induced products which have beta-carotenoid for anti-aging cream, orange pigments which prevent production of ROS which causes the cell damage, then other similar pigments and anti-oxidant agents (Agarwal et al., 2023).

FUTURE PROSPECTS AND RESEARCH DIRECTIONS GENETIC ENGINEERING ENHANCEMENTS

The use of advanced gene editing tools such as CRISPR-Cas9 allows precise modifications of marine endophyte genomes to enhance pigment production. This includes the upregulation of pigment biosynthetic pathways or the introduction of novel biosynthetic genes from other organisms. By identifying and modifying key enzymes and regulatory genes involved in pigment biosynthesis, researchers can optimize metabolic pathways to increase yield and efficiency. This involves creating genetic circuits that ensure maximum flux through pigment-producing pathways.

Researchers developed a reliable way to use CRISPR-Cas9 gene editing in the fungus *Fusarium oxysporum*, which is known for affecting plants. To do this, they used a special tag (called a nuclear localization sequence or NLS) from the fungus's own histone H2B gene to help guide the Cas9 protein into the nucleus, where the DNA is. They combined this NLS with the Cas9 protein, purified it, and then introduced it into fungal cells (specifically, protoplasts—cells without a cell wall) using a method called PEG-mediated transformation. To show that the system works, they first made mutations in two well-known fungal genes, URA5 and URA3. Then, they tested a more advanced step: using homology-directed repair (HDR) to insert a new DNA marker into the FoBIK1 gene. This gene is important because it controls the production of beavering, a red pigment made by the fungus. This targeted editing was successful in up to 50% of the treated cells, which shows the method is quite effective (Zhang et al., 2020).

SYNTHETIC BIOLOGY APPROACHES

Synthetic biology enables the design of marine endophytes with custom-built metabolic pathways tailored for specific pigment production. This can involve the synthesis of entirely new pigments by combining biosynthetic genes from different organisms. Development of modular genetic constructs that can be easily inserted, removed, or swapped in marine endophytes to streamline the testing and optimization of various pigment production pathways.

ENHANCED PIGMENT PROPERTIES

Genetic modifications can be aimed at producing pigments with enhanced stability under extreme environmental conditions, or with specific functional properties

such as increased solubility, bioavailability, or bioactivity. By exploring the genetic potential of marine endophytes and manipulating their metabolic pathways, entirely new pigments with unique chemical structures and properties can be discovered.

CONCLUSION

Harnessing pigment production from marine endophytes stands as an exciting and rapidly advancing frontier for industrial applications due to the outstanding bioactivities and uniqueness of these compounds. Marine endophytes have the ability to thrive in extremely and nutrient-deprived habitats, thereby imparting remarkable stability, antioxidant properties, and activities against various pathogenic microorganisms to their pigment products. Consequently, these attract applications in different industries such as pharmaceuticals, cosmetics, food, and agriculture. Marine endophytes can produce bioactive pigments even in the most stressful of environments. Therefore, marine endophytes represent a source of sustainable and eco-friendly alternative dyes over synthetic dyes that are known to have both environmental and health issues. However, massive hurdles remain due to the arduous isolation and cultivation of marine endophytes and optimization of pigment production on an industrial scale. Innovations in biotechnology can be achieved through metabolic engineering, genetic modification, and fermentation optimization. These improve yield, stability, and diversity while lowering the cost of pigment production. This review calls for further exploration in the biodiversity of pigments originating from marine endophytes and their biosynthetic pathways toward functional applications. Targeted research could lead to breakthroughs on safer and more sustainable alternatives against synthetic counterparts. Overcoming current limitations will help industries seize the potential of marine-derived pigments to cater to the rising demand for natural, biodegradable, and environmentally friendly products from consumers. The future for research on marine endophytes is bright with promises of revolutionizing multiple sectors from novel pharmaceuticals to enhanced aesthetic and functional cosmetics and food products.

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REFERENCES

- Ababutain, I. M., Aldosary, S. K., Aljuraifani, A. A., Alghamdi, A. I., Alabdallal, A. H., Al-Khalidi, E. M., Aldakeel, S. A., Almandil, N. B., AbdulAzeez, S., & Borgio, J. F. (2021). Identification and Antibacterial Characterization of Endophytic Fungi from *Artemisia sieberi*. *International Journal of Microbiology*, 2021, 6651020. <https://doi.org/10.1155/2021/6651020>
- Adhikari, P., & Pandey, A. (2021). Antimicrobial compound production by pigment producing endophytic bacterium (*Burkholderia sp.* GBPI_TWL) isolated from *Taxus wallichiana* Zucc. *Biologia*, 76(11), 3567–3578. <https://doi.org/10.1007/s11756-021-00886-8>
- Affat, S. (2021). *Classifications, Advantages, Disadvantages, Toxicity Effects of Natural and Synthetic Dyes: A review*. 8, 130–135.
- Afzal, I., Shinwari, Z. K., Sikandar, S., & Shahzad, S. (2019). Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants. *Microbiological Research*, 221, 36–49. <https://doi.org/10.1016/j.micres.2019.02.001>
- Agarwal, H., Bajpai, S., Mishra, A., Kohli, I., Varma, A., Fouillaud, M., Dufossé, L., & Joshi, N. C. (2023). Bacterial Pigments and Their Multifaceted Roles in Contemporary Biotechnology and Pharmacological Applications. *Microorganisms*, 11(3), Article 3. <https://doi.org/10.3390/microorganisms11030614>
- Ahmadi, A., Anvar, S. A. A., Nowruzi, B., & Golestan, L. (2024). Effect of phycocyanin and phycoerythrin on antioxidant and antimicrobial activity of refrigerated low-fat yogurt and cream cheese. *Scientific Reports*, 14(1), 27661. <https://doi.org/10.1038/s41598-024-79375-2>
- Ashfaq, M., Ali, Q., Haleem, A., Ullah, A., Umar, A., Ullah, I., & Ahmed, S. (2022). Orange-Brown Pigment Production from an Endophytic Fungus *Aspergillus Sp. N11* and its Potential Pharmaceutical Applications. <https://doi.org/10.21203/rs.3.rs-1126132/v1>
- Banerjee, D., Dey, B., Halder, S., & Pati, B. (2016). Optimization of red pigment production by endophytic *Pezizula sp.* BDF9/1 through OVAT and RSM methodology. *International Journal of Current Research*, 8, 28194–28201.
- Beaver, R. C., & Neufeld, J. D. (2024). Microbial ecology of the deep terrestrial subsurface. *The ISME Journal*, 18(1), wrae091. <https://doi.org/10.1093/ismejo/wrae091>
- Benkhaya, S., M'rabet, S., & El Harfi, A. (2020). Classifications, properties, recent synthesis and applications of azo dyes. *Heliyon*, 6(1), e03271. <https://doi.org/10.1016/j.heliyon.2020.e03271>
- Calado, M. da L., Silva, J., Alves, C., Susano, P., Santos, D., Alves, J., Martins, A., Gaspar, H., Pedrosa, R., & Campos, M. J. (2021). Marine endophytic fungi associated with *Halopteris scoparia* (Linnaeus) Sauvageau as producers of

- bioactive secondary metabolites with potential dermocosmetic application. *PLOS ONE*, 16(5), e0250954. <https://doi.org/10.1371/journal.pone.0250954>
- de Melo Pereira, D. Í., Gurgel, R. S., de Souza, A. T. F., Matias, R. R., de Souza Falcão, L., Chaves, F. C. M., da Silva, G. F., Martínez, J. G., de Lima Procópio, R. E., Fantin, C., & Albuquerque, P. M. (2024). Isolation and Identification of Pigment-Producing Endophytic Fungi from the Amazonian Species *Fridericia chica*. *Journal of Fungi*, 10(1), Article 1. <https://doi.org/10.3390/jof10010077>
- DeBritto, S., Gajjar, T. D., Satapute, P., Sundaram, L., Lakshminantha, R. Y., Jogaiyah, S., & Ito, S. (2020). Isolation and characterization of nutrient dependent pyocyanin from *Pseudomonas aeruginosa* and its dye and agrochemical properties. *Scientific Reports*, 10(1), 1542. <https://doi.org/10.1038/s41598-020-58335-6>
- Di Salvo, E., Lo Vecchio, G., De Pasquale, R., De Maria, L., Tardugno, R., Vadalà, R., & Cicero, N. (2023). Natural Pigments Production and Their Application in Food, Health and Other Industries. *Nutrients*, 15(8), Article 8. <https://doi.org/10.3390/nu15081923>
- El-Fouly, M. Z., Sharaf, A. M., Shahin, A. A. M., El-Bialy, H. A., & Omara, A. M. A. (2015). Biosynthesis of pyocyanin pigment by *Pseudomonas aeruginosa*. *Journal of Radiation Research and Applied Sciences*, 8(1), 36–48. <https://doi.org/10.1016/j.jrras.2014.10.007>
- Elkhateeb, W., & Daba, G. (2022). Marine Endophytes a Natural Novel Source for a Treasure of Bioactive Compounds. *Journal of Advances in Microbiology*, 5, 1–5. <https://doi.org/10.24966/AMR-694X/100018>
- Gaber, D. A., Berthelot, C., Camehl, I., Kovács, G. M., Blaudez, D., & Franken, P. (2020). Salt Stress Tolerance of Dark Septate Endophytes Is Independent of Melanin Accumulation. *Frontiers in Microbiology*, 11. <https://doi.org/10.3389/fmicb.2020.562931>
- Golinska, P., Wypij, M., Agarkar, G., Rathod, D., Dahm, H., & Rai, M. (2015). Endophytic actinobacteria of medicinal plants: Diversity and bioactivity. *Antonie van Leeuwenhoek*, 108(2), 267–289. <https://doi.org/10.1007/s10482-015-0502-7>
- Hagaggi, N. Sh. A., & Abdul-Raouf, U. M. (2023). Production of bioactive β -carotene by the endophytic bacterium *Citricoccus parietis* AUCs with multiple *in vitro* biological potentials. *Microbial Cell Factories*, 22(1), 90. <https://doi.org/10.1186/s12934-023-02108-z>
- Hashimoto, H., Uragami, C., & Cogdell, R. J. (2016). Carotenoids and Photosynthesis. *Sub-Cellular Biochemistry*, 79, 111–139. https://doi.org/10.1007/978-3-319-39126-7_4
- Jagannathan, S. V., Manemann, E. M., Rowe, S. E., Callender, M. C., & Soto, W. (2021). Marine Actinomycetes, New Sources of Biotechnological Products. *Marine Drugs*, 19(7), 365. <https://doi.org/10.3390/md19070365>
- Jia, M., Chen, L., Xin, H.-L., Zheng, C.-J., Rahman, K., Han, T., & Qin, L.-P. (2016). A Friendly Relationship between Endophytic Fungi and Medicinal Plants: A Systematic Review. *Frontiers in Microbiology*, 7. <https://doi.org/10.3389/fmicb.2016.00906>
- Kanade, Y., Mohan, W., & Patwardhan, R. (2022). Violacein: A Promising Bacterial Secondary Metabolite. *Research Journal of Chemistry and Environment*, 26, 165–177. <https://doi.org/10.25303/2606rjce165177>
- Kazi, Z., Hungund, B. S., Yaradoddi, J. S., Banapurmath, N. R., Yusuf, A. A., Kishore, K. L., Soudagar, M. E. M., Khan, T. M. Y., Elfakhany, A., & Buyondo, K. A. (2022). Production, Characterization, and Antimicrobial Activity of Pigment from *Streptomyces* Species. *Journal of Nanomaterials*, 2022(1), 3962301. <https://doi.org/10.1155/2022/3962301>
- Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. *Food & Nutrition Research*, 61(1), 1361779. <https://doi.org/10.1080/16546628.2017.1361779>
- Kramar, A., Ilic-Tomic, T., Petkovic, M., Radulović, N., Kostic, M., Jovic, D., & Nikodinovic-Runic, J. (2014). Crude bacterial extracts of two new *Streptomyces* sp. Isolates as bio-colorants for textile dyeing. *World Journal of Microbiology & Biotechnology*, 30(8), 2231–2240. <https://doi.org/10.1007/s11274-014-1644-x>
- López-Gutiérrez, N., Romero-González, R., Vidal, J. L. M., & Frenich, A. G. (2013). Analysis of triphenylmethane dyes in seafood products: A review of extraction methods and determination by liquid chromatography coupled to mass spectrometry. *Analytical Methods*, 5(14), 3434–3449. <https://doi.org/10.1039/C3AY40485D>
- Mabuza, L., Sonnenberg, N., & Marx-Pienaar, N. (2023). Natural versus synthetic dyes: Consumers' understanding of apparel coloration and their willingness to adopt sustainable alternatives. *Resources, Conservation & Recycling Advances*, 18, 200146. <https://doi.org/10.1016/j.rcradv.2023.200146>
- Mani, I., Thangavel, M., Surendrababu, A., Sneha, M. J. X., Rajagopal, R., Alfarhan, A., Ponnuraj, N., & Pandi, M. (2024). Unveiling the Bioprospecting Efficacy and Textile Dyeing of a Novel Endophytic Mycobial Red Pigment. *Indian Journal of Microbiology*, 64(2), 618–634. <https://doi.org/10.1007/s12088-024-01211-y>
- Meeraj Fatima., & K. Anuradha. (2022). Isolation, characterization and optimization studies of bacterial pigments. *Journal of Pure and Applied Microbiology*, 16(2), 1039-1048. <https://doi.org/10.22207/JPAM.16.2.28>
- Megala, B., & Vasan, P. T. (2023). Diversity of Endophytic Bacteria from Marine Associated Plant Leaves. *Indian Journal of Science and Technology*, 16(23), 1726–1732. <https://doi.org/10.17485/IJST/v16i23.88>
- Mishra, R. C., Kalra, R., Dilawari, R., Deshmukh, S. K., Barrow, C. J., & Goel, M. (2021). Characterization of an Endophytic Strain *Talaromyces assiutensis*, CPEF04 With Evaluation of Production Medium for Extracellular Red Pigments Having Antimicrobial and Anticancer Properties. *Frontiers in Microbiology*, 12. <https://doi.org/10.3389/fmicb.2021.665702>
- Mudaliar, S. B., & Bharath Prasad, A. S. (2024). A biomedical perspective of pyocyanin from *Pseudomonas aeruginosa*: Its applications and challenges. *World Journal of Microbiology and Biotechnology*, 40(3), 90. <https://doi.org/10.1007/s11274-024-03889-0>
- Muñoz-Miranda, L. A., & Iñiguez-Moreno, M. (2023). An extensive review of marine pigments: Sources, biotechnological applications, and sustainability. *Aquatic Sciences*, 85(3), 68. <https://doi.org/10.1007/s00027-023-00966-8>
- Mushtaq, S., Shafiq, M., Tariq, M. R., Sami, A., Nawaz-ul-Rehman, M. S., Bhatti, M. H. T., Haider, M. S., Sadiq, S., Abbas, M. T., Hussain, M., & Shahid, M. A. (2023). Interaction between bacterial endophytes and host plants. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.1092105>
- Nawaz, A., Chaudhary, R., Shah, Z., Dufossé, L., Fouillaud, M., Mukhtar, H., & ul Haq, I. (2021). An Overview on Industrial and Medical Applications of Bio-Pigments Synthesized by Marine Bacteria. *Microorganisms*, 9(1), Article 1. <https://doi.org/10.3390/microorganisms9010011>
- Numan, M., Bashir, S., Mumtaz, R., Tayyab, S., Rehman, N. U., Khan, A. L., Shinwari, Z. K., & Al-Harrasi, A. (2018). Therapeutic applications of bacterial pigments: A review of current status and future opportunities. *3 Biotech*, 8(4), 207. <https://doi.org/10.1007/s13205-018-1227-x>
- Paillié-Jiménez, M. E., Stincone, P., & Brandelli, A. (2020). Natural Pigments of Microbial Origin. *Frontiers in Sustainable Food Systems*, 4. <https://doi.org/10.3389/fsufs.2020.590439>
- Pauer, H., Haridoim, C. C. P., Teixeira, F. L., Miranda, K. R., Barbirato, D. da S., Carvalho, D. P. de, Antunes, L. C. M., Leitão, Á. A. da C., Lobo, L. A., & Domingues, R. M. C. P. (2018). Impact of violacein from *Chromobacterium violaceum* on the mammalian gut microbiome. *PLoS ONE*, 13(9), e0203748. <https://doi.org/10.1371/journal.pone.0203748>
- Peyrat, L.-A., Tsafantakis, N., Georgousaki, K., Ouazzani, J., Genilloud, O., Trougakos, I. P., & Fokialakis, N. (2019). Terrestrial Microorganisms: Cell Factories of Bioactive Molecules with Skin Protecting Applications. *Molecules*, 24(9), Article 9. <https://doi.org/10.3390/molecules24091836>
- Phan, K., Van Den Broeck, E., Van Speybroeck, V., De Clerck, K., Raes, K., & De Meester, S. (2020). The potential of anthocyanins from blueberries as a natural dye for cotton: A combined experimental and theoretical study. *Dyes and Pigments*, 176, 108180. <https://doi.org/10.1016/j.dyepig.2019.108180>
- Poddar, K., Padhan, B., Sarkar, D., & Sarkar, A. (2021). Purification and optimization of pink pigment produced by newly isolated bacterial strain *Enterobacter* sp. PWN1. *SN Applied Sciences*, 3(1), 105. <https://doi.org/10.1007/s42452-021-04146-x>
- Rajendran, P., Somasundaram, P., & Dufossé, L. (2023). Microbial pigments: Eco-friendly extraction techniques and some industrial applications. *Journal of Molecular Structure*, 1290, 135958. <https://doi.org/10.1016/j.molstruc.2023.135958>
- Rather, L. J., Mir, S. S., Ganie, S. A., Shahid-ul-Islam, & Li, Q. (2023). Research progress, challenges, and perspectives in microbial pigment production for industrial applications—A review. *Dyes and Pigments*, 210, 110989. <https://doi.org/10.1016/j.dyepig.2022.110989>
- Saubenova, M., Rapoport, A., Venkatachalam, M., Dufossé, L., Yermekbay, Z., & Oleinikova, Y. (2024). Production of Carotenoids by Microorganisms. *Fermentation*, 10(10), Article 10. <https://doi.org/10.3390/fermentation10100502>
- Sebola, T. E., Uche-Okereafor, N. C., Mekuto, L., Makatini, M. M., Green, E., & Mavumengwana, V. (2020). Antibacterial and Anticancer Activity and Untargeted Secondary Metabolite Profiling of Crude Bacterial Endophyte Extracts from *Crinum macowanii* Baker Leaves. *International Journal of Microbiology*, 2020(1), 8839490. <https://doi.org/10.1155/2020/8839490>
- Sen, T., Barrow, C. J., & Deshmukh, S. K. (2019). Microbial Pigments in the Food Industry—Challenges and the Way Forward. *Frontiers in Nutrition*, 6. <https://doi.org/10.3389/fnut.2019.00007>
- Sharma, N., Shekhar, P., Kumar, V., Kaur, H., & Jayasena, V. (2024). Microbial pigments: Sources, current status, future challenges in cosmetics and therapeutic applications. *Journal of Basic Microbiology*, 64(1), 4–21. <https://doi.org/10.1002/jobm.202300214>
- Sharma, R., & Ghoshal, G. (2021). Characterization and cytotoxic activity of pigment extracted from *Rhodotorula mucilaginosa* to assess its potential as bio-functional additive in confectionary products. *Journal of Food Science and Technology*, 58(7), 2688–2698. <https://doi.org/10.1007/s13197-020-04775-x>
- Simsek Geyik, M., Efe, D., & Gormez, A. (2024). Identification of Bacteria Producing Red Pigments and Their Application in the Textile Industry. *Arabian Journal for Science and Engineering*. <https://doi.org/10.1007/s13369-024-09290-1>
- Singh, R., & Dubey, A. K. (2018). Diversity and Applications of Endophytic Actinobacteria of Plants in Special and Other Ecological Niches. *Frontiers in Microbiology*, 9. <https://doi.org/10.3389/fmicb.2018.01767>
- Soliev, A. B., Hosokawa, K., & Enomoto, K. (2011). Bioactive Pigments from Marine Bacteria: Applications and Physiological Roles. *Evidence-Based*

- Complementary and Alternative Medicine: eCAM*, 2011, 670349. <https://doi.org/10.1155/2011/670349>
- Srilekha, V., Krishna, G., Sreelatha, B., Jagadeesh Kumar, E., & Rajeshwari, K. V. N. (2024). Prodigiosin: A fascinating and the most versatile bioactive pigment with diverse applications. *Systems Microbiology and Biomanufacturing*, 4(1), 66–76. <https://doi.org/10.1007/s43393-023-00192-1>
- Suwannarach, N., Kumla, J., Nishizaki, Y., Sugimoto, N., Meerak, J., Matsui, K., & Lumyong, S. (2019). Optimization and characterization of red pigment production from an endophytic fungus, *Nigrospora aurantiaca* CMU-ZY2045, and its potential source of natural dye for use in textile dyeing. *Applied Microbiology and Biotechnology*, 103(17), 6973–6987. <https://doi.org/10.1007/s00253-019-09926-5>
- Suwannarach, N., Kumla, J., Watanabe, B., Matsui, K., & Lumyong, S. (2019). Characterization of melanin and optimal conditions for pigment production by an endophytic fungus, *Spissiomycetes endophytica* SDBR-CMU319. *PLoS ONE*, 14(9), e0222187. <https://doi.org/10.1371/journal.pone.0222187>
- Tuli, H. S., Chaudhary, P., Beniwal, V., & Sharma, A. K. (2015). Microbial pigments as natural color sources: Current trends and future perspectives. *Journal of Food Science and Technology*, 52(8), 4669–4678. <https://doi.org/10.1007/s13197-014-1601-6>
- Velmurugan, P., Venil, C. K., Veera Ravi, A., & Dufossé, L. (2020). Marine Bacteria Is the Cell Factory to Produce Bioactive Pigments: A Prospective Pigment Source in the Ocean. *Frontiers in Sustainable Food Systems*, 4. <https://doi.org/10.3389/fsufs.2020.589655>
- Venil, C. K., Dufossé, L., & Renuka Devi, P. (2020). Bacterial Pigments: Sustainable Compounds With Market Potential for Pharma and Food Industry. *Frontiers in Sustainable Food Systems*, 4. <https://doi.org/10.3389/fsufs.2020.00100>
- Venkatachalam, M. (2024). Pigment Production Using Submerged Fermentation. *Fermentation*, 10(2), Article 2. <https://doi.org/10.3390/fermentation10020091>
- Vesterlund, S.-R., Helander, M., Faeth, S. H., Hyvönen, T., & Saikkonen, K. (2011). Environmental conditions and host plant origin override endophyte effects on invertebrate communities. *Fungal Diversity*, 47(1), 109–118. <https://doi.org/10.1007/s13225-011-0089-x>
- White, J. F., Kingsley, K. L., Zhang, Q., Verma, R., Obi, N., Dvinskikh, S., Elmore, M. T., Verma, S. K., Gond, S. K., & Kowalski, K. P. (2019). Review: Endophytic microbes and their potential applications in crop management. *Pest Management Science*, 75(10), 2558–2565. <https://doi.org/10.1002/ps.5527>
- Wu, W., Chen, W., Liu, S., Wu, J., Zhu, Y., Qin, L., & Zhu, B. (2021). Beneficial Relationships Between Endophytic Bacteria and Medicinal Plants. *Frontiers in Plant Science*, 12. <https://doi.org/10.3389/fpls.2021.646146>
- Yanti, N. A., Jamili, Ardiansyah, & Anwarrudin, S. (2021). Antibacterial activity of fungi endophytic isolated from leaves the mangrove *Acanthus ilicifolius* L. *Journal of Physics: Conference Series*, 1899(1), 012015. <https://doi.org/10.1088/1742-6596/1899/1/012015>
- Zhai, Y., Bai, J., Chang, P., Liu, Z., Wang, Y., Liu, G., Cui, B., Peijnenburg, W., & Vijver, M. G. (2024). Microplastics in terrestrial ecosystem: Exploring the menace to the soil-plant-microbe interactions. *TrAC Trends in Analytical Chemistry*, 174, 117667. <https://doi.org/10.1016/j.trac.2024.117667>
- Zhang, S., Guo, F., Yan, W., Dai, Z., Dong, W., Zhou, J., Zhang, W., Xin, F., & Jiang, M. (2020). Recent Advances of CRISPR/Cas9-Based Genetic Engineering and Transcriptional Regulation in Industrial Biology. *Frontiers in Bioengineering and Biotechnology*, 7. <https://doi.org/10.3389/fbioe.2019.00459>