Biological Aspects of Marine Biofilm Bacterial Pigment

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Abstract

Marine bacterial species contribute to a significant part of the oceanic population, which substantially produces biologically effectual moieties having various medical and industrial applications. The use of marine-derived bacterial pigments displays a snowballing effect in recent times, being natural, environmentally safe, and health beneficial compounds. Although isolating marine bacteria is a strenuous task, these are still a compelling subject for researchers, due to their promising avenues for numerous applications Due to their beneficial properties, including anticancer, antibacterial, antioxidant, and cytotoxic actions, marine-derived bacterial pigments were desirable in the food, pharmaceutical, textile, and cosmetic industries. Marine bio-pigments are preferred over synthetically produced colored compounds due to their biodegradability and higher environmentally friendly nature. Besides that, hazardous effects associated with the consumption of synthetic colors further substantiated the use of marine dyes as color additives in industries as well. Herein, we have reviewed the potential of different bacterial species isolated from the marine environment in diverse studies that produce bioactive pigments with potential commercial applications, in addition to the biosynthesis and physiological roles of associated pigments. The chemical structures of the bioactive compounds are also discussed.

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Abstract

Marine bacterial species contribute to a significant part of the oceanic population, which substantially produces biologically effectual moieties having various medical and industrial applications. The use of marine-derived bacterial pigments displays a snowballing effect in recent times, being natural, environmentally safe, and health beneficial compounds. Although isolating marine bacteria is a strenuous task, these are still a compelling subject for researchers, due to their promising avenues for numerous applications Due to their beneficial properties, including anticancer, antibacterial, antioxidant, and cytotoxic actions, marine-derived bacterial pigments were desirable in the food, pharmaceutical, textile, and cosmetic industries. Marine biopigments are preferred over synthetically produced colored compounds due to their biodegradability and higher environmentally friendly nature. Besides that, hazardous effects associated with the consumption of synthetic colors further substantiated the use of marine dyes as color additives in industries as well. Herein, we have reviewed the potential of different bacterial species isolated from the marine environment in diverse studies that produce bioactive pigments with potential commercial applications, in addition to the biosynthesis and physiological roles of associated pigments. The chemical structures of the bioactive compounds are also discussed.

Key words: biofilm, quorum sensing, pigments, biomedical application, textile

Introduction

The Earth's covered by 70% of water molecules, which comprise 80% of all biological organisms. Aquatic vegetation is more diversified than their terrestrial counterparts. Bacteria play a vital role in the marine environment. They drive biogeochemical cycles, deliver resources and bring energy to higher tropical levels. Marine biofilm easily colonies on man-made surfaces, quickly inducing corrosion, biofouling, and possibly affecting polyethylene plastic buoyancy (de Carvalho, 2018). Bacteria within biofilm are shown to control physiological co-operation and spatial organization in order to increase metabolic potential and resistance to fluctuations in the local environment (Chew & Yang, 2015). In general, the interaction of microbial cells with the substrate surface under specific physico-chemical and nutritional conditions at the seawater surface interface contributes substantially to the initiation and success of microbial surface colonization in marine environments. Physico-chemical properties of the substratum such as surface free energy, electrostatic charge, hydrophobicity, wettability, roughness, micro topography, vulnerability to wear (corrosion) and surface chemo-dynamic properties of surface conditioning, nutrient enrichment, and charge accumulation or alternation may influence the ability of microorganisms to adhere to a particular abiotic surface. Chemical interactions of solutes with the substratum's surface, biological interactions of microbial cells with the surfaces of other microbial cells, and specific gene regulation at the population and community levels are all investigated. It plays a main role in microbial surface colonization, modification of surface physicochemical properties, structured biofilm development, and the establishment and maturation of functional communities (Dang & Lovell, 2016). One of the strategies that microbes use to survive is believed to be on biotic and abiotic surfaces because they offer significant benefits, such as (i) Increased access to nutrients, (ii) Protection against toxins and antibiotics, (iii) Maintenance of extracellular enzyme activities, and (iv) Protection from predation. In marine environments, bacteria play many roles, including driving the biogeochemical cycles, supplying materials and bringing energy to higher tropical levels Marine bacterial communities are known to play a key role in the management of ecological and biogeochemical processes as well as in the development of the ecosystem. Some microbes could have a huge potential for producing a wide range of pigments and biomolecules. Seasonal and geographical conditions influence natural characteristics of marine bacteria such as color, therapeutic capabilities, and nutrient synthesis such as vitamins, proteins, and lipids (C. Ramesh et al., 2020).

Marine biofilms, also known as micro fouling, are organized communities of mixed organisms that, along with diatoms and bacteria, are found in the ocean. Quorum sensing is a bacterial cell-to-cell communication process that regulates numerous important aspects of biofilm growth and other phenomena. Quorum sensing controls a variety of processes by acting as a simple communication network by secreting, accumulating, and recognizing low molecular mass signaling compounds, which leads to the expression of phenotypes that improve nutrient access, colonisation rigidity, and community resistance to hostile environments (Salta et al., 2013). Lanosterol identified from pigmented marine biofilm bacteria*Kocuria rosea* Ac. No KC505190 exhibits anti-biofilm activity and anti-quorum sensing activity against dominated micro-fouling bacterial groups by targeting their signaling protein molecules. Lanosterol exhibited repellent activity by altering the signal transduction pathways for modifying bacterial quorum sensing communication and thus prevented biofilm formation. From the docking study, it has been found that the lanosterol prefer hydrophobic nature to improve the binding contacts of signaling proteins (Balasubramanian et al., 2018). There is a huge potential for marine bacterial populations to synthesize a variety of bioactive components, such as pigment molecules. The synthesized pigments by bacteria are known as secondary metabolites that help them survive in extreme environments. In order to survive in harsh environments, stress, and cell damage, bacteria must evolve cell adaption mechanisms, one of which is the synthesis of pigment. In frigid climates like the Antarctic region, bacteria are exposed at even low temperatures and continuous UV radiation creates pigment synthesis (carotenoid, prodigiosin etc.), which protects cells from UV irradiation and allows bacteria to survive in extreme environments. A quorum-sensing mechanism regulates the production of these pigment molecules. In the marine environment, pigments such as carotene, quinones, melanins, prodiginines, tambjamine and violacein have been reported so far such as Cytotoxicity, antioxidant, antibacterial, antimalarial, anticancer, antitumor and antifouling characteristics etc., (C. Ramesh et al., 2019). In this review, we pointed the importance of bioactive natural pigments produced by marine biofilm bacteria.

Biofilm structure

Ecosystems are composed of a variety of energetic microhabitats where microbial communities interact ideally ”as metabolically interdependent groups”. Bacteria colonise microhabitats compatible with their physiologic and metabolic needs, which depend upon their neighbouring bacteria, and this may influence the spatial structure of the community. Biofilm communities are composed of either interspecies or lipids. The extracellular polymeric substance provides protection to the microorganism not only from altered pH, osmolarity, and nutrient scarcity but also blocks the access of bacterial biofilm communities to antibiotics and therefore the host’s immune cells (Sharma et al., 2019) (Fig 1. Structure of Biofilm Formation).

Extracellular polymeric substances

Extracellular polymeric substances formation in microorganisms may be impacted by changes in saltiness, weight, supplement levels, etc., in the marine environment (Bhaskar & Bhosle, 2005).The cells can be a part of irreversibly attached surfaces (i.e., those not expelled by tender washing), can begin organic processes, form tiny scale colonies, and deliver the animate polymers that are characterised as biofilm formation. The biofilm structure is maintained by extracellular polymeric substances, which are biopolymers made primarily of polysaccharides, protein, lipids, and nucleic acids (Donlan, 2001).

The extracellular polymeric substances (EPS) matrix of biofilm affords a third-dimensional architectural framework that permits the movement of cells relative to different microbes. Furthermore, positioning among sharp geochemical gradients will increase the secretion of metabolic products such as uronic acids, D-glucuronic acid, and D-galacturonic acid. The extracellular polymeric substances enable self-corporation of cells into localised groups and give biofilm cells superior functionality for trapping various organics, localising their digestion through extracellular enzymes, coordinating cell-to-cell communication, facilitating gene-exchange and bestowing a level of physical stability (Decho & Gutierrez, 2017).Monomers known as monosaccharides that are connected to one another via glycosidic bonds can be contained in a polysaccharide chemical structure. They can be created from a single type of monosaccharide in homo polysaccharides or from a variety of types, typically up to 10, in hetero polysaccharides. The distribution of monosaccharides might be random or in blocks, as well as an ordinary repeating unit. Sulfates, phosphates, acetates, ethers, amino acids, lactates, and pyruvates are a few examples of the inorganic and natural substituents that can enhance the polysaccharide backbone, which can be straight or branched (Casillo et al., 2018). Substances related to exo-polymeric matrices have a couple of functions. Some of these functions are signalling molecules or messengers, and others are power and nutrient reserves with a critical function in polymer degradation and floor adhesion (Mavrodi et al., 2010).

Quorum sensing

Bacterial individual cells can use quorum detection to coordinate with others in their colony in order to perform constitutive tasks, especially those involving substances can assist in a variety of ways, including survival, competence, bioluminescence, biofilm formation and even sporulation. Signal molecules are released by bacteria in quorum sensing systems in a cell density-dependent manner, and signal transduction is induced via cascading quorum sensing regulatory proteins. Small molecule QSIs are one type, which can be extracted from natural resources or synthesised chemically, and quorum quenching enzymes, which include acylases, lactonases that target acyl-homoserine lactones (AHLs) as signalling molecules, AI-2 kinases that target furanosyl borate ester (auto inducer 2, AI-2) as signalling molecules, and so on (J. Zhao et al., 2019). Signal molecules bind to response regulators, which then start transcription of Quorum Sensing regulated genes, allowing for population-wide transcription. The *Lux* A-E, LuxG, *Lux* I, and *Lux* R genes were found to be involved in these phenomena and were classified as bi-directionally transcribed operons. *Lux* A and *Lux* B are two proteins that make up the luciferase enzyme, which creates light. The *Lux* C-D-E proteins make the luciferase substrates, while *Lux* G is a flavin reductase. The *Lux* I and *Lux* R proteins, on the other hand, generate the most interest in quorum sensing research. *Lux* R is the bacteria's diffusible signal receptor, and the AI synthase *Lux* I is responsible for AI creation. The AIs bind to the *Lux* R receptors, which operate as transcription factors and stimulate the production of all lux genes when they reach a threshold concentration in the immediate environment of bacterial cells (indicating an increase in cell abundance). The AI designation is given to the five diffusible signals because they promote their own production through the automatic induction of *Lux* I (Lami, 2019) (Fig 2. Mechanism of Quorum Sensing).

General Aspects of Pigment

A chemical compounds called pigments reflect light in the visible part of the spectrum. The chromophore is a highly delocalized component in a molecule that is frequently responsible for absorbing light in the visible area and giving the compound a colourful appearance, is what causes the colour to be created. Carbon-carbon double bonds, benzene rings, carbon-oxygen double bonds, lone pairs of nitrogen or oxygen and other forms of groups may all play a role in the delocalization. An electron's energy and excitement are captured by this structure and transferred to an upper orbital. The unabsorbed energy is reflected and/or refracted in order to be captured by the eye. The eye then converts this energy into neural impulses, which the brain interprets as colour (Silva et al., 2021).

Market demand for microbial pigments

Microbial pigment production has significantly increased in geometric proportions through current genetic engineering techniques. Microbes also have an upper hand in versatility and productivity over higher forms of life in the industrial-scale production of natural pigments and dyes. The fermentation process has been increased by genetic engineering and further research for nontoxic microbial pigments can make quantum leaps in the economics of microbial pigment production (Galasso et al., 2017). People all around the world have been affected by synthetic food colouring agents because of the negative impact on synthetic pigments. There is a need for natural pigments from biological organisms, especially marine biofilm bacterial communities. To expand the availability of natural colourants derived from various natural resources world-wide. Over the past few years, a major trend that has influenced pigment production has been the increase in globalisation, reorganization, and internationalisation. Global Industry Analysts predicts that demand for organic pigments and dyes will exceed 10 million tonnes by 2017. Initially dominated by suppliers from the UK, Switzerland, and Germany, the global dye manufacturing business later transitioned to Asia over the previous 20 years (Venil et al., 2013). But still, there is scanty data available on the market price of food-grade microbial pigments. Only a few pigments, such as beta-carotene, astaxanthin, and Monascus, are available on the market. Due to a lack of research reports on their cost and demand, it is becoming more challenging to estimate the actual global market demand for microbial pigments (Chatragadda & Dufossé, 2021).

Bacterial pigments from marine environment

Nature produces many pigments from a variety of resources, including plants animals and microorganisms. These pigments have been used as a potential material to replace synthetic dyes nowadays. Photo-pigments produced by microorganisms are preferred than the plant producing pigments because of their stability and feasibility of culturing. Among microbes, bacteria have tremendous potential for producing a variety of biproducts in which pigments are the major constituents (Abdulkadir, 2017). Marine bacteria are an important source of natural product discovery with a success rate up to four times higher than other naturally derived chemicals due to their extensive biodiversity and genetic capacity, which can contribute to the synthesis of novel bioactive pigments (C. Ramesh et al., 2019). The complicated "quorum sensing" process in the marine environment which mediates the production of these pigments, it can also produce when exposed to various stress situations in natural environment conditions. The reason for their selection is that marine microbial pigments have the ability to survive in extremely acidic or alkaline environments (pH4, > 9), extreme temperatures (2–15 °C and 60–110 °C) and insufficient nutrient availability. Halophilic archaea are widely distributed in the marine ecosystem. In addition to their capacity to withstand osmolytes (such as 2-sulfo-trehalose) or high ionic strength, pigmented compounds from marine archaea are also classified due to their ability to tolerate hyper-saline and basic pH environments. These pigments can be extensively used in a variety of bio-medical and bio-industrial sectors, including the textile, food, pharmaceutical, and cosmetic industries (e.g., fluorescence-based indicator) (Nawaz et al., 2021). Marine bacterial pigments are a current area of research because of their anti-microbial, anti-cancer, photoprotective, anti-parasitic and immunosuppressive characteristics. Marine bacteria synthesise a number of pigments, including carotene, melanin, phenazine, pyrrole, violacein, and quinones (Velmurugan et al., 2020) (Fig 3. Types of Marine Bacterial Pigment) (Table. 1).

Carotene

Carotenoids are a type of pigment that ranges in colour from red to yellow and are widely dispersed in bacteria, algae, fungi, and plants. Carotenoids are a class of lipid-soluble compounds linked to the lipidic fractions that are sensitive to oxygen, heat and light (Kirti et al., 2014). Carotenoid serves as a significant part in the photosynthetic process. It absorbs light energy ranging from 300 to 600 nm to drive the photosynthetic process (Kusmita et al., 2017). The production of carotenoids by using some marine yeast (*Rhodotorula* spp.) and some filamentous fungi (*M. purpureus*) is capable of synthesizing specific types of carotenoids (torularhodin, -carotene and torulene) that have shown pro-vitamin and antioxidant properties. They have been used as food colourants, cosmetics, and feed additives, and their other biological importance is given in Table. 2 (Velmurugan et al., 2020). Furthermore, carotenoids can act as shelters for photosynthetic organisms to protect them from hazardous exposure (Kusmita et al., 2017). From a chemical point of view, carotenoid is a polyisoprenoid compound with two main groups: Carotenes are hydrocarbon carotenoid compounds made up of carbon and hydrogen atoms, whereas xanthophylls are oxygenated hydrocarbon derivatives with one oxygen functional moieties such as hydroxyl, keto and epoxy, methoxy, or carboxylic acid groups. Carotenoids are not only beneficial for pigmentation, but they also offer unique photochemical properties that provide the basis for their application as nutritional components, vitamin A precursor, prevention of human diseases like cancer, and an industrial perspective (Kirti et al., 2014).

Marine carotenoids can be used as skin photo protection against the damaging effects of UV radiation or as a nutraceutical/cosmeceutical ingredient to treat oxidative stress-related illnesses because they have potent antioxidant, healing, antiproliferative, and anti-inflammatory properties. Some carotenoid compounds are produced by marine species known as astaxanthin (red pigment), and they possess significant anti-free radical and pro-oxidant activity. Fucoxanthin is one of the most prevalent carotenoids in nature, especially in the marine environment, and it accounts for around 10% of total carotenoid production. Carotenoids like fucoxanthin, zeaxanthin, and lutein have antioxidant capabilities like ROS scavenging, DNA damage protection, protein and lipid oxidation protection. Canthaxanthin is a carotenoid that is derived from crustaceans and algae and can be used as anticancer agent in human colon adenocarcinoma cells, human and murine melanoma cells (SK-MEL-2, JB/MS, and B16F10), and fibro sarcoma cells (SK-MEL-2, JB/MS, and B16F10) (PYB6) (Galasso et al., 2017).

Phenazine

Streptomyces (terrestrial), *Pseudomonas* (ubiquitous),*Actinomycetes* (terrestrial and aquatic), *Pelagibacter*(aquatic) and *Vibrio* (aquatic) produce phenazines under the control of a quorum sensing mechanism. Phenazines are redox-active, small nitrogen-containing aromatic compounds that are used in a variety of applications (Velmurugan et al., 2020). The colour intensity ranges from blue to green to purple to yellow to red to brown. More than 50 nitrogen-containing heterocyclic pigments of bacterial origin are found in naturally occurring phenazines. Their hues are determined by their absorption spectra, which contain two peaks in the UV range and at least one peak in the visible range. Due to their capacity to undergo cellular redox cycling in the presence of oxygen and reduce NADH and NADPH to induce the formation of harmful superoxide and hydrogen peroxide, almost all phenazines are generally detrimental to the growth of bacteria and fungi. *Pantoea agglomerans* produces phenazines on apple blooms that help to control the phytopathogenic *Erwinia amylovora* , which causes fire blight (Mavrodi et al., 2010).

Phenazine physiological action is linked to redox homeostasis, which increases ATP synthesis and membrane potential maintenance (Glasser, 2017). From a biotechnological standpoint, phenazines' physicochemical features, such as their oxidation–reduction (redox) properties, vivid pigmentation, and ability to alter colour with pH and redox state, are driving their continued study. Phenazines are still employed for a variety of purposes, including as electron acceptors and donors, fuel cell components, environmental sensors and biosensors, and as core components of anticancer drugs (Pierson & Pierson, 2010).

Prodigiosin

Prodigiosin is a blood-red coloured molecule that has antimicrobial, chemotherapeutic and immunological suppressive properties through a variety of mechanisms, including decoupling H/Cl-transporters, regulating cell pH, and cleaving DNA in the presence of copper (Velmurugan et al., 2020). It is a red pigment identified from*Serratia, Pseudomonas* and *Streptomyces* that is a secondary metabolite alkaloid and it possesses a unique tripyrrole chemical structure. Prodigiosin is a non-diffusible red pigment produced by the enzymatic condensation of 2-methyl-3-amylpyrrole with 4-methoxy-2, 2-'-bipyrrole-5-carboxyaldehyde, resulting in the tripyrrole derivative 2-methyl-3-amyl-6methoxyprodigiosene (Ahmed et al., 2021). Prodigiosin is also soluble in chloroform, methanol, acetonitrile and DMSO; it is moderately soluble in alcohol and ether. *S. marcescens* is a gram-negative, rod-shaped bacterium that belongs to the*Enterobacteriaceae* family and is known for its capacity to produce red pigment prodigiosin (J. Zhao et al., 2019).

Prodigiosin was also toxigenic to chick embryos and demonstrated cytotoxic activity via oxidative DNA breakage, which was particularly effective against melanoma and liver cancer cells. Apoptosis was also triggered by Prodigiosin in human haematological cancer cell lines, such as acute T-cell leukaemia, promyelocytic leukaemia, myeloma, Burkitt lymphoma cells, and B-and T-cells from B-cell chronic lymphocytic leukaemia (Sakai-Kawada et al., 2019). Temperature influences prodigiosin formation in S. marcescens, with temperatures above 37°C significantly suppressing it. Traditional media for *S. marcescens*strains' production of prodigiosin are complex media with a wide range of nutrients. Certain nutrients, such as thiamine and ferric acid, are essential for prodigiosin formation, whereas phosphate, adenosine triphosphate, and ribose hinder prodigiosin production. The textile business is one of the world's fastest-growing industries. Using statistical models such as Response Surface Methodology and Plackett-Burman Design, it accounts for 14 percent of total industrial production in India and roughly 30 percent of total exports that have the potential to be used as a dye in the textile sector (Krishna et al., 2011). The pigment exhibits antifungal, antibacterial, algicidal, antiprotozoal, antimalarial, immunosuppressive, and anticancer properties, but its significance in the physiology of generating strains is unknown. The antimicrobial activity of purified Prodigiosin isolated from *Serratia sp.* PDGS120915 against *Bacillus cereus, Bacillus subtilis, Listeria monocytogenes, Enterococcus faecalis, Staphylococcus aureus, Klebsiella pneumoniae, Escherichia coli, Salmonella typhimurium* and *Pseudomonas aeruginosa* (Poddar et al., 2021). Inhibition of the Wnt/-catenin signalling pathway and anticancer action in breast cancer cells, as well as reactivation of p53 family-dependent transcriptional activity in p53-deficient human colon cancer cells, are both possible effects of prodigiosin (J. Zhao et al., 2019).

Violacein

The violet pigment violacein is an indole derivative isolated primarily from bacteria of the genus *Chromobacterium* , which live in tropical and subtropical soil and water (Soliev et al., 2011). Bacteria which are found in a variety of natural environments, including marine, freshwater, and soil environments, could be able to produce violacein pigment. This bisindole is a secondary metabolite associated with biofilm production in the majority of violacein-producing bacterial strains isolated from nature. Violacein synthesis by *C. violaceum*has been shown to be a useful indicator of quorum-sensing molecules and their inhibitors, and it is easy to monitor. The secondary metabolite violacein acts as a toxic sentinel, protecting against a variety of potential bacterial predators and competitors (Choi et al., 2015).*Janthinobacterium lividum* and *Chromobacterium violaceum*had antipredator activity against bacterivorous nanoflagellates, indicating a protective function (Chatragadda & Dufossé, 2021).*Pseudoalteromonas luteoviolacea* is the sole marine bacterium producing violet pigment. *Shewanella violacea* , a deep-sea microorganism isolated from Ryukyu Trench sediments at a depth of 5110 m, also produced a violet pigment that was recently demonstrated to be a new alkylated indigoidine. The bacteria were isolated from seawater at Cape Muroto in Kochi Prefecture, Japan. Among the bacteria isolated, 13 strains of gram negative, rod-shaped bacteria produced a purple pigment similar to violacein (Yada et al., 2008).

Furthermore, violacein is extremely important in cosmetics, textiles, agriculture, and drug discovery. In the pharmaceutical industry, violacein has been used as an immunosuppressive, antinociceptive, analgesic, and antipyretic. According to animal studies, violacein pigment has been applied in ulcer rat models; it decreased gastrointestinal inflammation, perhaps through COX-1-mediated mechanisms. On the other hand, when violacein was injected directly into the intra-peritoneal cavity, it was discovered to have immune modulatory effects through controlling cytokine production; it let down the expression of IL-6 and TNF but increased the expression of IL-1. Non-specific toxicity is normally a drawback of chemotherapeutics, but violacein has been shown to induce apoptosis and have anti-tumor activity against unrepeatable particular tumour lamina lines, such as cancer lamina lines. Violacein seems to have antibiotic potential because of its strong antibacterial properties. Additionally, when combined with other antibiotics, the impact is more successful at killing bacteria than using antibiotics alone (Choi et al., 2015). Anti-protozoan, anti-cancer, anti-viral, antibacterial (both G+ and G-), and antioxidant properties have been discovered. *Staphylococcus aureus, Neisseria meningitidis, Streptococcus* sp*., Bacillus*sp*, Mycobacterium* and *Pseudomonas* , among others is all inhibited by the antibacterial action. Based on these characteristics, violacein appears to be commercially viable for medicinal applications, and it has even been proposed for use in dermatology. Due to its toxicity in VERO and FRhK-4 cells, it has been claimed that violacein should be considered an in vitro genotoxic chemical to mammalian cells, although more research is needed before making any conclusions on violacein's future therapeutic potential (Hakvåg et al., 2009).

Quinones

Quinones are secondary metabolites that can be found in bacteria, plants and a variety of other organisms (McErlean & Moody, 2007). Quinones, which have been isolated from the marine environment and are bioactive coloured molecules with an aromatic ring structure, have derivatives that range in colour from yellow to red (Soliev et al., 2011). Benzoquinones, naphthoquinones, and anthraquinones are the three primary classes of quinones, with 1, 2, and 3 ring structures, respectively. The fundamental subunit of quinone molecules is benzoquinone. Natural quinones are a vast class of aromatic chemicals found in a wide range of organisms, including algae, fungus (including lichens), bacteria, flowering plants, and arthropods (Dulo et al., 2021). The methanolic extract of*Lenzites betulina* yielded two free radical scavenging quinones, betulinans A and B. These free radical scavengers have the potential to defend against a variety of diseases, including atherosclerosis, diabetes, rheumatoid arthritis, and cancer. Himalomycins A and B are two quinone antibiotics that are derived from the *Streptomyces*isolate B6921. They are effective against *Bacillus subtilis, Staphylococcus aureus* and *Escherichia coli* germs (Gopal et al., 2013).

Quinones such as 2-hydroxy-9, 10-anthraquinone and naphthoquinone have been obtained from bacteria such as *Streptomyces olivochromogenes*and *Streptomyces* sp. They are used in energy harvesting and storage in areas such as artificial photosynthetic platforms and dye-sensitized solar cells, among others (Dulo et al., 2021). For thousands of years, humans have been fascinated by naturally occurring quinones, which have vibrant hues and the potential to be used as dyes and medications. Quinone derivatives, which have 1, 4-benzoquinone as a subunit, have a wide range of medicinal uses, including antibacterial, anticancer and antimalarial properties. In the laboratory (McErlean & Moody, 2007). Embelin (2, 5-dihydroxy-3-undecyl-1, 4-benzoquinone) has been shown to have anticancer and antioxidant characteristics. Quinones have antiviral, anti-infective, antibacterial, insecticidal and anticancer properties. They are also used as natural and synthetic colours and pigments in many industries (Soliev et al., 2011).

Melanin

Melanins are macromolecules that are synthesised during phenolic and/or indolic chemicals being oxidatively polymerized. These hydrophobic pigments are negatively charged, which are found throughout the biological system in a wide range and take part in processes like structure, colouring, free radical scavenging, radiation resistance, and thermoregulation. Many bacteria obtained from nature, including*Bacillus, Aeromonas* , *Rhizobium* and *Streptomyces* , have been shown to synthesis of melanin using the copper-containing enzyme tyrosinase (monophenol monooxygenase EC 1.14.18.1) (Wang et al., 2020). Bacterial melanin is produced by the usage of the enzyme tyrosinase, which oxidises into L-tyrosine and then converts to L-3, 4-dihydroxyphenylalanine. Finally, the transformed melanin synthesis takes place through the oxidoreduction process with a colour range of black to brown (Velmurugan et al., 2020). Melanin is the most stable, soluble, biochemically resistant, negatively charged, hydrophobic, high molecular weight, amorphous substance, but it is insoluble in common organic solvents, aqueous acid and water. There are three types of melanin based on colour and structural classes: (i) eumelanins (ii) pheomelanins (iii) allomelanins are colour pigments that range from black to brown in colour and that are synthesised via the standard. Pheomelanins are brown, red or yellow coloured pigments which are produced in the course of oxidation of tyrosine and/or phenylalanine to dihydroxyphenylalanine (DOPA) and dopaquinone. Pheomelanin results from cysteinylation of DOPA and these are sulphur-containing compounds. Allomelanins include nitrogen-free heterogeneous groups of polymers formed from catechol precursors. They are found in microorganisms and plants, whereas eumelanins and pheomelanins are found in animals only (Tarangini & Mishra, 2013). Microorganisms used melanin to protect themselves from heat, chemical (heavy metals and oxidising agents), enzymatic lysis, alveolar macrophages. There is a wide range of applications by using melanin in the fields of antimicrobial, antiviral, anticancer, antioxidant and anti-inflammation assays. Melanin has a high absorbing capacity of electromagnetic radiation, viz., visible light, ultraviolet radiation, and X-rays because of this property, the pharmaceutical and cosmetic industries use it in huge amounts. It has the ability to bind heavy metals and radionuclides (Wang et al., 2020), Which is used in the recycling of heavy metal-contaminated waste water. The mass production of melanin pigment is in high demand due to its significant bioactive potential properties and capacity to be employed in a wide range of applications. Furthermore, marine biological organisms as a major source for the synthesis of melanin pigment is an intriguing choice for both researchers and industries for its increased number of characteristics, including being safe, easily degradable and eco-friendly without causing severe side effects (Elsayis et al., 2022).

Biological application of bacterial pigments

Microorganism (fungi, yeasts and bacteria) are abundant in nature; the advantages of pigment synthesis from microorganisms include easy and rapid growth in a low-cost culture medium. Generally, bacterial pigments are used in cosmetics, food, pharmaceuticals and textile industries. Microbes producing natural colour molecules such as bacteriochlorophylls, carotenoids, flavins, indigoids, melanins, phenazines, monazines, prodigiosin, quinones, and violacein use them as by-products. The major requirements for various biotechnological applications in commercial businesses are pigment resources, production rate, transportation, pricing, sustainability, palatability, durability, effectiveness, legislative and regulatory permission and customer demand (C. H. Ramesh et al., 2017). Colourful and weather-resistant pigment-producing microorganism carbon sources like red rice, wine and red bean curd are used for the production of microbial pigments. For example, microbial colourants are already used in the fish business to increase the pink colour of farmed salmon (Soliev et al., 2011).The usage of ?- Carotene in vegetable oils as a solution or suspension in margarine colouring, baked goods and emulsions used in prepared foods or micro-encapsulated beadlets. It's also used in drinks like orange juice, confectionery and other ready-to-eat meals. Due to photosensitivity associated with quinidine consumption, which absorbs the hazardous short wavelength part of the light spectrum, carotenoids have been shown to protect against genetic disorders like erythropoietic protoporphyria (EPP) and erythema (skin reddening) (Kirti et al., 2014).

Prodigiosin is a critical bioactive compound with common applications in the food, pharmaceutical, cosmetic and textile industries. Prodigiosin has a broad range of biological activities, including antibacterial, antifungal, and antimalarial properties (Y. Zhao et al., 2020). The bacteria that produce prodigiosin and violacein offer strong defence and deterrence against bacterivores like protozoa and worms, as well as survival advantages against rivals and predators. They also offer selection advantages versus other bacteria in the area. Cancer is the world's second greatest cause of death, and despite the development of new therapies for specific malignancies, it remains as deadly as ever. Prodigiosin has been shown to kill human cancer cell lines by a process known as programmed cell death, or apoptosis. In addition to human lung cancer cells, gastric cancer cells, multidrug-resistant breast cancer cells, colorectal cancer cells, and glioblastoma multiform cancer cells in chronic lymphocytic leukaemia. This pigment has a suppressive effect on T-cell proliferation while having no effect on B-cell proliferation (Choi et al., 2021).

The UV absorption range of 290 to 320 nm was boosted by violacein, indicating that adding it to other sunscreen components could boost the protective factors (SPF). Aloevera leaf extract and *Cucumis sativus,* both of which have photo protective properties are included as well. The properties of violacein stated above suggest that it could be used as a photo protectant in biomedical applications. The purple colour of violacein, which is used in the textile industry, is a distinguishing property of this pigment made from growing *Chromobacterium* and*Janthinobacterium.* It is a specific culture used for dyeing fibrous materials and nylon textiles that has larvicidal and pupicidal effects on some insects. By suppressing the growth of pathogenic fungus and parasitic nematodes that cause plant damage, it was also effective in controlling microdochium, stem rot, damping off fungus, and damping-off of bean sprouts. Plant mycosis and plant-parasitic nematode diseases can be prevented with insecticides containing violacein and its derivatives (Choi et al., 2020).

Quinones are used for scent, flavour, defence, signalling, colour, and energy transduction, as well as acting as an intermediary between a plant and its environment. Antifungal, antibacterial, antioxidant, anti-cancer, anti-inflammatory, laxative, anti-allergens, and anti-moth activities of natural quinone components have found applications in pharmacology for promoting cytoprotection in humans. It is also utilised as histology stains and insect repellents, as well as in engineering and technology for metallic corrosion protection, pH indicators, and industrial colouring agents. Quinone dyes have been used as sensors, pigments, inks, and dyes for leather, wood, medicine, food and textiles as well as for histological staining, rust prevention on metal surfaces, and increasing the conversion efficiency of solar cells (Dulo et al., 2021).

Factors influencing pigment production

A range of factors, including species composition and relative abundance, biological productivity, water chemistry, and geographic location, may affect the pigment production of marine microbial communities. These variables include light intensity and spectral composition (mediated by lake depth, water-column transparency, and other variables like the duration and extent of winter weather (Hodgson et al., 2004). Due to their impact on the economy and practicability of any pigment production process, the optimization of microorganism growth conditions, particularly physical and nutritional parameters, is essential (Gopal et al., 2013). The temperature at which microbial pigments are produced varies greatly depending on the type of microbe, as well as the carbon supply (glucose, fructose, lactose, maltose, galactose, etc.) and nitrogen source (depending on the microorganism). Minerals play an important part in the synthesis of pigments (Susmita Mishra, 2014)

Conclusion and Future Perspective

This review concludes that the bacterial pigments which are used in an assortment of applications in the food, drug and textile industries. The pigments from bacteria can play an indirect role in the conservation of plant and animal resources by substituting pigment screening. Researchers and the food sector are currently looking for natural colouring substances that are derived from marine microorganisms due to their ecological value. According to this review, pigments generated from marine biofilm bacteria have been used in a wide range of industries. In addition, the pigments could be used in the agricultural production, fertiliser and seed dressing industries. The research reports from pigments produced by marine bacteria are very scanty compared to terrestrial bacteria. Overall, this review of marine bioactive pigments and their pharmaceutical uses reveals the significance of identifying fresh marine bacterial compounds. Such substances have a wide range of physiologically active properties and keep offering promising opportunities both for fundamental scientific research and biomedical study. Future studies should focus on determining the simplest method for collecting microbial pigments in order to expand their industrial applications. Accordingly, it is necessary to take into account a number of operational parameters that could cause a disparity due to the development and alteration of a new process by using inexpensive agricultural waste as a substrate in the future to identify high quality production of pigments. Future research should focus on a variety of methods that could lower manufacturing costs and boost yields for pigments on a broad scale

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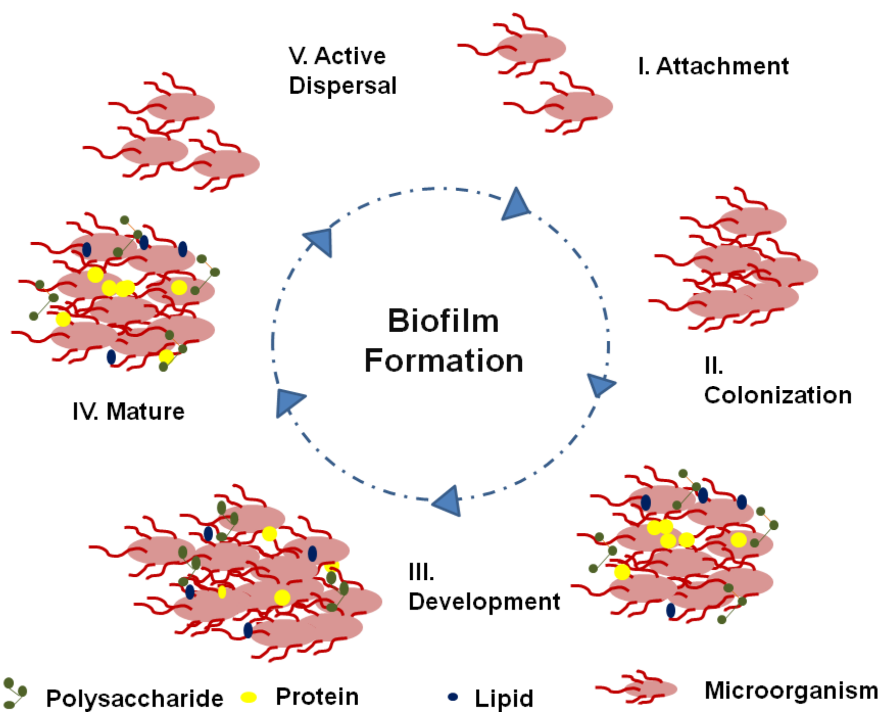

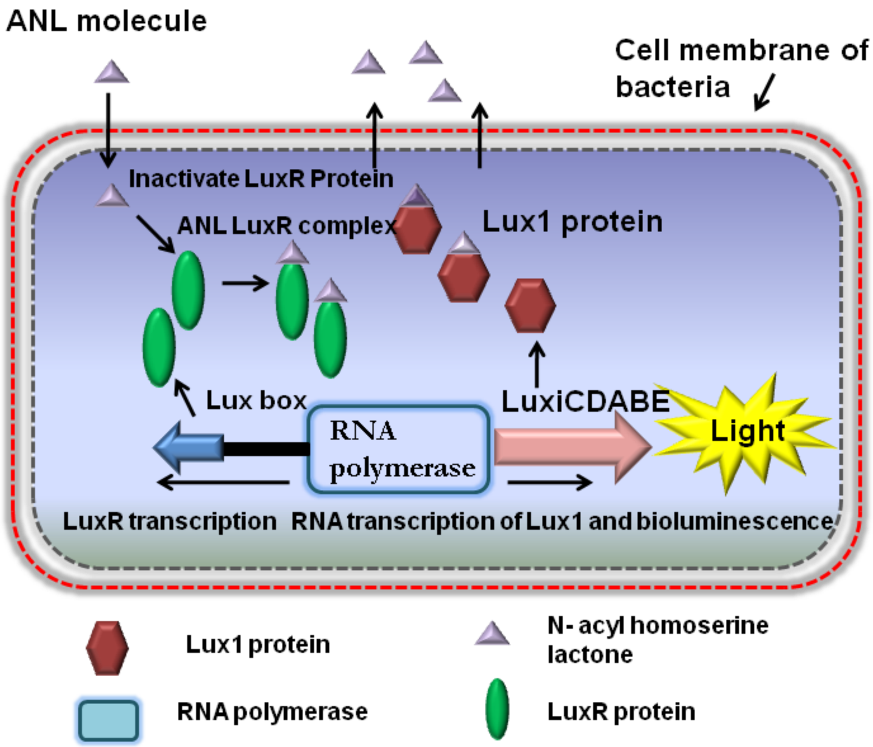

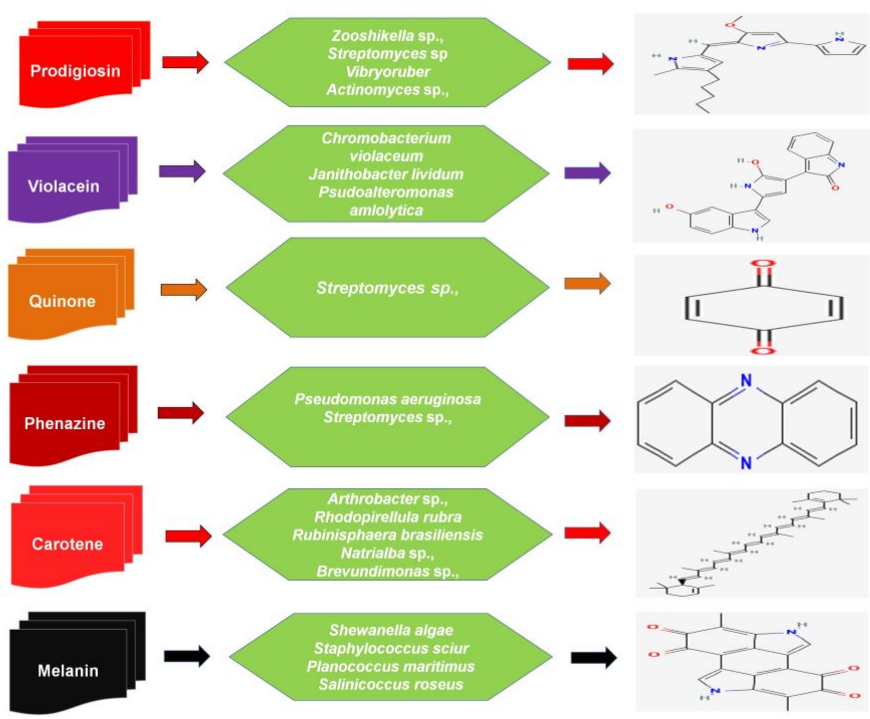

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