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Study of prodigiosin pigments from *Streptomyces* and their varied applications

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ABSTRACT

Prodigiosin is an important red tripyrrole pigment generated by *Streptomyces* spp., recognized for its strong antimicrobial, anticancer, and immunomodulatory properties, positioning it as a valuable natural bioactive compound for use in pharmaceutical and industrial sectors. The diverse bioactivities and natural origin of prodigiosin establish it as a promising candidate for sustainable applications in therapeutics, natural dyes, and food or cosmetic colorants. This review utilizes a systematic narrative synthesis of published articles to thoroughly examine environmental sources, isolation workflows, culture optimization, analytical characterization, and applications of prodigiosin derived from *Streptomyces*. This work integrates literature from various ecosystems, including marine and terrestrial environments, while also focusing on specialized habitats. It elaborates on pretreatment methods, selective media, fermentation strategies, and analytical techniques, including UV–Vis, GC–MS, LC–MS, NMR, FT-IR, and HPLC. Despite thorough investigation, there are still gaps in comprehending the genomic regulation of prodigiosin biosynthesis, especially within marine *Streptomyces*. Additionally, issues related to pigment stability, solubility, and scalable production continue to impede industrial and clinical applications.Future investigations should concentrate on genomic and metabolic engineering to clarify regulatory networks, enhance fermentation and bioprocessing at scale, and create stable formulations to enable broader biomedical and industrial applications. Meeting toxicological and regulatory requirements is essential for ensuring safe translation. Broadening the investigation into less-explored environments could uncover new variants of prodigiosin with enhanced characteristics. This collaborative approach will elevate prodigiosin from a fascinating microbial metabolite to a practical and sustainable foundation for therapeutics and colorants.

KEY WORDS

Streptomyces; Prodigiosin; Microbial pigments; Fermentation; Actinomycetes; Chemotaxonomy; LC–MS; Bioactivity

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Introduction

Actinomycetes are Gram-positive, sporulating, aerophilic bacteria found in soil and marine ecosystems. They produce secondary metabolites with various medical values, including antibiotics, antiprotozoal, anticholesterolemic, antihelminth, anticancer, and immunosuppressant effects [1]. Actinomycetes contribute around 45% of the total bioactive compounds, with *Streptomyces* species being responsible for a substantial proportion. These compounds have led to the development of various clinically useful drugs, including antitumor agents [2].

Actinomycetes and microbial pigments are essential sources of bioactive secondary metabolites, with the potential to reduce production costs and environmental impact [3]. Microbial pigments, such as carotenoids, flavonoids, tetrapyrroles, and astaxanthin, are of greater importance due to their natural character and safety. They are used in natural food colorants due to their antioxidant and anticancer properties [4].

Prodigiosin pigments represent a category of naturally occurring red pigments primarily synthesized by diverse *Streptomyces* species and other microorganisms. The unique tripyrrole chemical structure of these secondary metabolites has garnered significant interest, owing to their remarkable coloration and notable biological activities [5].

Prodigiosin, a naturally derived pigment with a unique tripyrrole structure, is used as a natural colorant in paper, candles , soap , and biodegradable ink. Its synthesis occurs through a bifurcated pathway, with precursors identified as acetate, serine, alanine, methionine, and proline. Prodigiosin compounds are alkaloid pigments obtained via microbial fermentation, noted for their bioactive properties such as antimicrobial, antifungal, immunosuppressive, and anticancer effects [6]. The diverse range of biological activities arises from their capacity to interfere with various cellular processes, making them potential candidates for applications in pharmaceuticals and industry [7].

Actinobacterial research studies have emphasized prodigiosin's potential applications in various domains, including medicine (cancer treatment and immune modulation), agriculture (biocontrol of plant pathogens), and food safety (as natural colorants and preservatives). Furthermore, their functions in environmental and biotechnological contexts spanning bioremediation to the management of microbial communities highlight the adaptability and significance of these pigments [8].

Even though our knowledge of *Streptomyces* prodigiosin biosynthesis has advanced, there are still unanswered questions, especially regarding the genomic analysis of strains originating from the marine sources and the identification of the distinct pigment gene clusters, regulatory networks, and environmental stimuli that affect production [9]. The structural and functional characteristics of many prodigiosin analogs are still unknown, and issues including pigment instability and

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limited solubility prevent broader use in industry and medicine. Future research should concentrate on uncovering the ecological and evolutionary distribution of pigmented Streptomyces in various environments, mining understudied *Streptomyces* genomes, improving metabolic and fermentation processes, and creating stable formulations for wider biomedical and industrial use [10].

The present review adopts a narrative synthesis approach, consolidating published literature to evaluate environmental sources, isolation methodologies, biosynthetic pathways, and diverse applications of *Streptomyces*-derived prodigiosin. Research across marine, terrestrial, and specialized habitats, as well as process optimizations including pretreatments, selective media, and fermentation were systematically assessed. Analytical tools such as UV–Vis, GC–MS, LC–MS, NMR, FT-IR, and HPLC were reviewed for pigment characterization. A particular research gap persists regarding the genomic analysis of marine *Streptomyces*, elucidation of regulatory pathways, and the stability and solubility of prodigiosin analogs, which currently limit large-scale industrial or clinical translation. Addressing these gaps would require in-depth genomic mining, advanced metabolic engineering, and the development of novel bioprocessing strategies.

Inclusion criteria comprised peer-reviewed articles and reviews focusing on the isolation, biosynthesis, optimization, and applications of prodigiosin derived specifically from 1 species, including studies spanning environmental and biotechnological relevance.

Exclusion criteria included non-English publications, studies not centered on *Streptomyces*-associated prodigiosins, research on synthetic pigments, and articles lacking experimental or methodological details.

Future research should focus not only on the genomic and metabolic enhancement of prodigiosin-producing strains for improved yield and stability, but also on the development of scalable, regulatory-compliant production models and the exploration of unexplored habitats for novel strains. This will facilitate broader biomedical, industrial, and environmental applications while providing sustainable alternatives to synthetic compounds. The sustainable utilization of *Streptomyces*-derived prodigiosin holds promise for future advances in colorant technology and therapeutic development, provided that rigorous toxicological and regulatory assessments are established.

Diversity

Marine ecosystems, covering over two-thirds of the earth's surface, are characterized by diverse conditions such as temperature, salinity, nutrient availability, oxygen levels, and pressure. These factors contribute to the rich microbial diversity in marine habitats and influence the genetic adaptation of marine actinomycetes, leading to the production of unique secondary metabolites. Samples were collected from various locations, including macroalgae, sediment, sponges, scleractinia corals, and coral reef environments [11].

Actinomycetes are present in all soil layers and are sensitive to acidity/low pH and waterlogged soil conditions. They are mesophilic and thermophilic species commonly present at 55-65℃ temperature. Soil samples were collected from various locations, including deserts, mountains, wooded regions, and mangrove forests [12].

The review aimed to describe the isolation of the red pigments produced by *Streptomyces* sp. from various soil samples, focusing on their red color reverse side pigments. The literature of this study can help researchers understand the genetic adaptations of marine actinomycetes and their potential applications in various ecosystems.

Sample collection

Marine sources included macroalgae from Northern Portugal, deep-sea sediments (≤2403 m) in the South China Sea, coral- and sponge-associated biota, and marine ranching sediments [13-17]. Terrestrial sources comprised deserts, wooded soils, mangroves, paddy fields, rhizospheres, and canals [18-23]. Special habitats included culture collections, plant seeds/oils, leaf litter, and bee pollen [24-27].

Pretreatment

Selective enrichment used heat (50–60 °C) and drying to suppress non-sporulating microbes as well as antibiotics/antifungals (nalidixic acid, cycloheximide, nystatin) [13, 16, 22, 23, 28]. Calcium carbonate was applied to soils/pollen prior to incubation to favor actinomycetes [21, 27].

Isolation

The isolation of actinomycetes, a group of gram-positive bacteria known for their ability to utilize a wide range of substrates, employs various general bacterial isolation techniques. These methods include serial dilution, pour plate techniques, streaking for purification, and centrifugation to separate microbial cells from soil particles [29]. Ravi and Jadeja emphasize that centrifugation followed by serial dilution of supernatants can significantly enhance the isolation of actinomycetes on agar plates [30].

In marine environments, specific media formulations have been utilized for the isolation of *Streptomyces* species. For instance, Girao et al. [13], utilized Actinomycete Isolation Agar (AIA) containing sodium acetate and other nutrients to isolate *Streptomyces* from tissue samples. Similarly, Song et al. [14], employed HRA medium, incubating sediment samples at 28°C for four weeks to achieve isolation. Abdelfattah et al. [16], described a method involving sponge samples homogenized in sterile water, followed by inoculation on yeast extract and malt extract media, resulting in red colony formation after 15 days of incubation. Zhang et al. [17], reported the isolation of actinomycetes from marine samples using Hopebio medium, while Shi et al. [15], isolated *Streptomyces* from coral samples using tryptic soy agar.

Terrestrial actinomycetes isolation has also been extensively studied. Abraham and Chauhan [26], isolated actinomycetes from leaf litter using starch casein nitrate medium, while Kazi et al. [23], utilized a similar approach with varying dilution factors on starch casein agar. Zhou et al. described a method involving Gao's No. 1 liquid medium for pigment extraction from actinomycetes [31]. Kramar et al. [19], focused on isolating prodigiosin-producing strains from wooded regions, and Bondkly et al. maintained pure cultures of actinomycetes on yeast agar medium [25].

In a broader context, Ramesh et al. [32], highlighted the use of various media, including marine and nutrient agar, for isolating pigment-producing actinomycetes from both biotic and abiotic samples. Sayed et al. and Vignesh et al. further explored the use of starch nitrate agar and actinomycetes isolation agar with antibiotics to enhance isolation efficiency [21, 28]. Additionally, Chakraborty et al. and Mokhnache et al.

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demonstrated the effectiveness of serial dilution techniques in isolating pigment-producing actinomycetes from soil samples [20, 27].

Overall, the literature indicates a diverse array of methodologies for the isolation of actinomycetes, with specific media formulations and incubation conditions tailored to the source of the samples, whether marine or terrestrial. These approaches are crucial for the discovery of novel actinomycetes with potential biotechnological applications. Serial dilution and selective media (e.g., Actinomycete Isolation Agar, Starch Casein Agar; prolonged incubation at 28–30 °C) facilitated recovery of red-pigmented Streptomyces. Matrix-specific media included histidine–raffinose agar for deep-sea sediments and yeast–malt extract/TSA for coral- and sponge-associated isolates [14-17] (Figure 1).

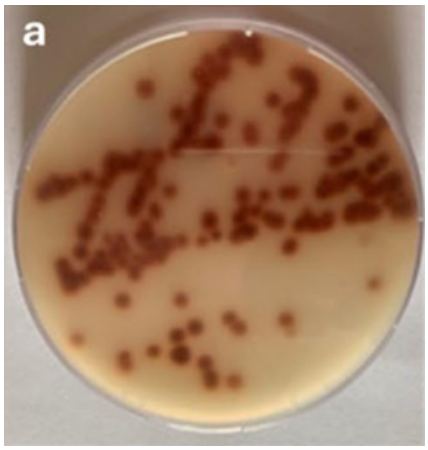

Figure 1. Representative red-pigmented *Streptomyces* colonies.

Production and Fermentation

Prodigiosin, typically a late-growth secondary metabolite, was produced in media such as yeast–malt extract, peptone–glycerol, and modified Luria–Bertani using inexpensive substrates (e.g., vegetable oils, cassava wastewater). *Streptomyces* tauricus accumulated predominantly intracellular pigment within mycelial pellets [31].

Prodigiosin, a secondary metabolite produced by various bacterial species, particularly from the genus *Streptomyces*, has outlined significant attention due to its potential applications in pharmaceuticals and biotechnology. The synthesis of prodigiosin is typically associated with the later stages of bacterial growth and is influenced by numerous environmental factors, including temperature, pH, and nutrient availability [33].

Recent studies have highlighted the feasibility of utilizing low-cost and environmentally friendly substrates for prodigiosin production. For instance, *Streptomyces* tauricus was cultivated using marine and terrestrial media, yielding significant amounts of red-pigmented extracts. In marine conditions, a specific medium comprising glucose, meat extract, and seawater was employed, resulting in a crude extract of 2.6 g after methanolic extraction [16]. Terrestrial cultivation methods included the use of Gao's liquid medium and starch casein broth, which facilitated the production of intracellular pigments [23, 31]. Furthermore, various fermentation techniques, such as submerged fermentation in yeast extract-malt extract broth, have been optimized to enhance pigment yield [27].

The optimization of cultural conditions is crucial for maximizing prodigiosin production. Factors such as incubation time, inoculum size, temperature, and pH have been systematically evaluated. Studies indicate that the optimal pH for pigment production is neutral (pH 7), while acidic and alkaline conditions significantly hinder synthesis [22]. Additionally, the presence of specific metal ions and carbon sources has been shown to influence pigment stability and yield. For example, the addition of certain fatty acids in mineral salt broth has been linked to enhanced production of prodigiosin-like pigments [25].

The stability of prodigiosin is notably affected by pH variations, with acidic conditions preserving their color, while neutral and alkaline environments lead to color loss [31]. Moreover, the pigment's resilience to temperature and UV exposure further underscores its potential for industrial applications [19].

Therefore, the production of prodigiosin is a multifaceted process influenced by various environmental and nutritional factors. The utilization of cost-effective substrates and the optimization of growth conditions are essential for enhancing pigment yield. Future research should focus on refining these methodologies and exploring the genetic and biochemical pathways involved in prodigiosin biosynthesis to unlock its full potential in biotechnological applications.

Optimization of pigment production

Key variables included incubation (3–12 days), inoculum size (2–8%), temperature (25–40 °C), initial pH (6–9), agitation, broth volume, and C/N/P sources [28]. Prodigiosin showed acid stability and thermotolerance (60–120 °C); Cu^{2+} decolorized, Fe^{2+}/Fe^{3+} shifted hue, while $Zn^{2+}/Mn^{2+}/Al^{3+}/Pb^{2+}$ had minimal impact [31]. Neutral pH (~7) and 28–30 °C frequently maximized yields; low-viscosity oilseed substrates (e.g., peanut) improved mass transfer [22, 25].

Molecular Systematics

The isolation of actinomycetes, a group of bacteria known for their significant role in natural product biosynthesis, can be enhanced through various pretreatment methods aimed at promoting their growth while minimizing the presence of competing microorganisms, particularly gram-negative bacteria. Both physical and chemical methods have been employed to achieve selective isolation of actinomycete species.

In marine environments, physical treatments such as incubating macerated tissues in a water bath at 58°C for 15 minutes have been shown to limit the occurrence of non-spore forming microorganisms and enhance the growth of slow-growing actinomycete strains, thereby increasing the success rate of antibacterial isolation [13]. Additionally, the incorporation of antibacterial and antifungal agents like nalidixic acid (50 µg/ml) and cycloheximide (75 µg/ml) into actinomycete media prepared with 50% sterilized seawater has proven effective in suppressing unwanted microbial growth [16].

In terrestrial settings, various physical pretreatment methods have been explored. For instance, air drying soil samples at 55°C for one hour has been utilized to inhibit the

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growth of bacteria and fungi [23]. The addition of nystatin (25 µg/ml) and nalidixic acid (10 µg/ml) to starch nitrate medium post-sterilization has also been reported to enhance actinomycete isolation by reducing microbial competition [22]. Other studies have indicated that drying soil samples at temperatures ranging from 50-60°C for 5-10 minutes can effectively reduce the proportion of non-actinomycete microorganisms [28]. Furthermore, to isolate specific pigments produced by *Streptomyces*, a vortexing step was employed to ensure an even distribution of the stock solution before inoculation [24]. The use of nalidixic acid and cycloheximide

The molecular systematics of red pigment-producing *Streptomyces* species has been extensively studied through the analysis of the 16S rRNA gene, which serves as a crucial marker for phylogenetic classification. DNA isolation and amplification of the 16S rRNA gene were performed using universal bacterial primers (27F and 1492R), followed by sequence analysis via the EzBioCloud server and phylogenetic reconstruction using MEGA version 11 [17]. 16S rRNA amplification (27F/1492R) with EzBioCloud/BLAST assignments and MEGA phylogenetics (NJ/ML/MP) positioned isolates within *Streptomyces*; genome-based ANI/AAI/dDDH refined species boundaries and supported novel taxa [15, 17]. Chemotaxonomy (LL-2,6-diaminopimelic acid; whole-cell sugars; polar lipids; menaquinones; fatty acids) distinguished close taxa [15, 25].

Phylogenetic studies revealed that strains such as *Streptomyces* sp. exhibit close relationships with other *Streptomyces* species, notably *Streptomyces colinus*, although the low bootstrap values (<70%) indicated some instability in the phylogenetic tree [17]. Further genomic analyses based on single-copy genes provided a more robust classification, identifying *Streptomyces flaveolus*, *Streptomyces ambofaciens*, and *Streptomyces lienomycini* as close relatives [17].

In the case of *Streptomyces manganisoli*, a nearly complete 16S rRNA gene sequence (1,432 bp) demonstrated a high similarity (99.5%) to *Streptomyces marincola*, suggesting they may represent the same species based on ANI, dDDH, and AAI thresholds [15]. Similarly, *Streptomyces fradiae* was confirmed as a potent isolate through phylogenetic analysis, showing 98% similarity with other strains [20].The identification of *Streptomyces phaeolivaceus* was achieved through ITS region sequencing, revealing a bootstrap value of 100% in relation to other *Streptomyces* isolates [28]. Moreover, the genetic analysis of red single colony isolates indicated significant identity with various *Streptomyces* species, leading to their designation as *Streptomyces* sp. [25]. Further investigations into *Streptomyces violaceoruber* indicated a close relationship with *Streptomyces anthocyanicus*, supported by genome sequencing and ANI analysis [13]. Distinct morphological and biochemical characteristics were noted in some strains, suggesting potential new species within the *Streptomyces* genus [35].

Chemosystematics of Red Pigment Producers

The chemotaxonomic analysis of red pigment-producing bacteria, specifically two strains of *Streptomyces* (P1 and P2), reveals significant differences in their cell wall composition and phospholipid profiles. Both strains exhibit a type I cell wall; however, P1 is characterized by the presence of LL-diaminopimelic acid, glutamic acid, glycine, and D-alanine, while P2 contains alanine, glycine, and lysine. The sugar composition also varies, with P1 containing mannose, ribose, and galactose, in contrast to P2, which includes glucose, galactose, mannose, and fucose. Furthermore, the phospholipid profiles differ, with P1 displaying a chemotype I pattern and P2 a phospholipid type 2 pattern, both lacking phosphatidylcholine and phosphatidylmethylethanolamine [25].

In a separate study, chemotaxonomic analyses of *Streptomyces marincola* and *Streptomyces specialis* highlighted differences in their cellular fatty acid compositions. *Streptomyces marincola* is predominantly composed of iso-C16:0 (37.7%) and C12:0 (13.1%), while *Streptomyces specialis* features iso-C16:0 (33.2%) and anteiso-C17:0 (19.3%). The polar lipid profiles of these strains also exhibit notable differences, particularly in the presence of unidentified phospholipids in *Streptomyces marincola*.

Characterization of Pigment

The characterization of pigments produced by *Streptomyces* species, particularly red pigments, has been extensively studied using various analytical techniques. Gas chromatography-mass spectrometry (GC-MS) analysis revealed the presence of multiple compounds in methanol-extracted pigments, identifying ten major components associated with *Streptomyces* sp. [22]. The GC-MS employed a temperature ramp from 100 °C to 250 °C, utilizing helium as carrier gas, and the chromatogram was matched against the NIST library for compound identification [21].

UV–Vis spectra exhibited λmax near 535 nm (prodiginines) with additional bands at 220–340 nm; AgNP conjugates showed 413–434 nm plasmon bands [23, 27]. GC–MS profiled constituent peaks; LC–MS/MS detected prodigiosin at m/z ~324 ([M+H]+); 1H/13C NMR resolved core motifs; FT-IR indicated OH, NH, CH, aromatic and COOH stretches; HPLC (C18, PDA) resolved prodiginine derivatives [16, 18, 20, 21, 22, 26].

Ultraviolet-visible (UV-Vis) spectroscopy further characterized these pigments, indicating their ability to sporulate and produce diffusible pigments in both solid and liquid media. The absorption maxima at 535 nm suggested the presence of prodigiosin-like pigments, while variations in absorption spectra were noted in different extracts [23, 28]. Additionally, UV-Vis analysis of silver nanoparticles synthesized from *Streptomyces* indicated characteristic absorption bands at 413 nm and 434 nm [27].

Nuclear magnetic resonance (NMR) spectroscopy was employed to analyze the purified pigments, revealing complex profiles indicative of prodigiosin-type compounds, although the exact structures remained undetermined due to spectral complexity [19]. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis of prodigiosin extracts demonstrated effective separation and identification of compounds, with a notable signal at m/z 324 [18].

High-performance liquid chromatography (HPLC) analysis of actinomycetes crude extracts identified two main peaks corresponding to prodigiosin derivatives, with characteristic UV-Vis absorbance between 300 to 400 nm [16]. Fourier-transform infrared (FT-IR) spectroscopy provided insights into the functional groups present in the isolated compounds,

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identifying hydroxyl, amine, and carboxylic groups, among others [20] (Figure 2).

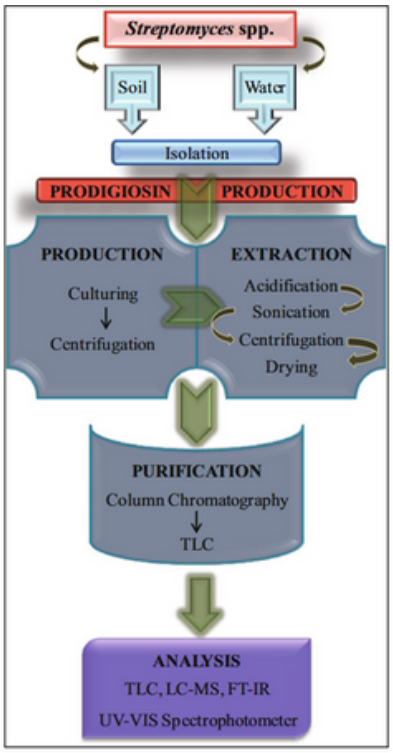

Figure 2. Flow diagram of depiction of Prodigiosin pigment synthesis and evaluation from *Streptomyces* species.

Applications of Red Pigment

Prodigiosin, a red pigment produced by certain bacterial species, particularly from the genus *Streptomyces*, has gained significant attention due to its diverse applications across multiple industries, including pharmaceuticals, food, textiles, and cosmetics. Its multifaceted biological properties, such as antimicrobial, immunosuppressive, antimalarial, antineoplastic, and anticancer activities, underscore its potential as a valuable biomolecule.

Research has demonstrated prodigiosin's efficacy against various cancer cell lines. For instance, studies have shown that prodigiosin inhibits the viability of HT1080, HEp-2, HeLa, and MCF-7 cell lines, with IC50 values ranging from 8.5 to 18.5 µg/mL, indicating its potential as an anticancer agent [18 ,26]. Further investigations revealed that prodigiosin significantly reduces cell viability in colon (HCT-116), liver (HEPG-2), and breast cancer (MCF-7) cell lines, with the most pronounced effects observed in MCF-7 cells [25]. These findings highlight prodigiosin's promise as a therapeutic agent in cancer treatment.

The exploration of marine pigmented bacteria, particularly from the Andaman Islands, has revealed a rich genetic diversity among *Streptomyces* species, suggesting the potential for discovering novel strains with valuable biomedical applications [32]. This genetic diversity may lead to the identification of new natural pigments suitable for food and pharmaceutical uses.

Prodigiosin's application in the textile industry has been explored through its use as a natural dye. Research indicates that pre-treatment with tannic acid enhances dye absorption and color fastness in fabrics such as cotton, wool, and polyester. This eco-friendly approach to textile coloration emphasizes the importance of optimizing dyeing conditions, including pH and temperature, to maximize effectiveness [28].

Prodigiosin's exhibit a range of therapeutic properties, including antifungal and antibacterial effects. Recent studies have suggested their potential use in treating gastric lesions, with ongoing research aimed at elucidating the gastroprotective mechanisms of prodigiosins in rat models [16, 36]. Additionally, the combination of prodigiosins with nanoparticles may enhance their antimicrobial efficacy against resistant strains [23].

In the cosmetic sector, prodigiosin has been incorporated into formulations such as lip balms, demonstrating stability in color and texture over extended periods. Stability tests indicate that these formulations maintain their properties under various conditions, suggesting their viability for commercial use [20, 21].

Prodigiosin's potential as an antibiofilm and antifouling agent has been explored, with compounds like napyradiomycin showing effectiveness against marine biofilm-forming bacteria. These findings suggest that prodigiosin-derived compounds could be developed into environmentally friendly antifouling products [34, 35]. The prodigiosin's diverse applications across various fields highlight its potential as a multifunctional biomolecule. Continued research into its properties and applications may lead to significant advancements in biotechnology, agriculture, and medicine.

Discussion

This synthesis highlights that source ecology, pretreatment, and media strongly condition prodigiosin discovery and yield. Neutral pH and mesophilic temperatures repeatedly maximize production, with oilseed substrates aiding oxygen and mass transfer. Pigment physicochemistry (acid stability, thermal/photostability, metal ion sensitivity) informs downstream processes in dyeing, food, and pharma. While in vitro cytotoxicity is promising, translation requires standardized potency assays, selectivity against normal cells, and ADME/tox studies. Genome-resolved taxonomy (ANI/AAI/dDDH) should be combined with chemotaxonomy to avoid misidentification in pigment producers. For manufacturing, fed-batch/bioreactor control of pH, phosphate limitation, and oxygen transfer likely improves titters, and low-cost agro-residues can reduce COGS [36].

The research conducted on the isolation and characterization of red pigments, specifically prodigiosin, from *Streptomyces* species highlights the significant bioactive potential of these actinomycetes. Known for their production of secondary metabolites with diverse biological activities, including antibacterial, antifungal, anticancer, and anti-inflammatory properties, *Streptomyces* were sourced from various environments such as marine, terrestrial, and specialized habitats [37].

To enhance the growth of actinomycetes while inhibiting competing microbes, pretreatment methods including heat, chemical additives (e.g., calcium carbonate), and antibiotics were employed. Isolation techniques utilized serial dilution and selective media, notably Actinomycetes Isolation Agar and Starch Casein Agar, to purify red pigment-producing colonies [38]. The optimization of prodigiosin production was meticulously studied under varying culture conditions, with

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optimal yields achieved at pH 7 and temperatures between 28–30°C, utilizing low-viscosity substrates [39].

Conclusion

Streptomyces-derived prodigiosin is a versatile, sustainable pigment with compelling antimicrobial and anticancer profiles and practical uses as a natural colorant and antifoulant. Continued work on strain improvement, process intensification, and regulatory toxicology will accelerate translation to textiles, cosmetics, foods, and therapeutics. Overall, these studies underscore the importance of molecular techniques in elucidating the phylogenetic relationships among red pigment-producing *Streptomyces* species, contributing to our understanding of their taxonomy and potential applications in biotechnology. Therefore, the integration of GC-MS, UV-Vis, NMR, LC-MS, HPLC, and FT-IR techniques has facilitated a comprehensive understanding of the chemical composition and functional properties of red pigments produced by *Streptomyces* species, highlighting their potential applications in various fields.

Disclosure Statement

The author does not have conflict of interest in this research.

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