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Microbial pigments as sustainable bio-products: Extraction techniques, optimization, and applications

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Abstract
The growing preference for natural and eco-friendly colorants has intensified research into microbial pigments as sustainable alternatives to synthetic dyes. Microorganisms such as fungi, bacteria, yeast, and algae are valuable sources of diverse bio-pigments, including carotenoids, melanin, prodigiosin, and polyketides like Monascus pigments. These compounds not only impart attractive colors but also exhibit antioxidant, antimicrobial, and anticancer properties. Efficient pigment extraction is essential for maximizing yield and purity, with conventional methods like solvent extraction increasingly complemented by enzyme-assisted, ultrasound, and supercritical fluid techniques. Extraction efficiency depends on culture parameters such as pH, temperature, substrate composition, and oxygen availability, which influence both pigment synthesis and stability. Recent advances in bioprocess optimization and green extraction methods have improved pigment recovery while reducing environmental impact. However, challenges remain in large-scale production, color stability, and regulatory approval for food applications. Overall, microbial color extraction represents a promising, sustainable, and multifunctional approach that aligns with global trends toward natural, health-promoting, and clean-label products.

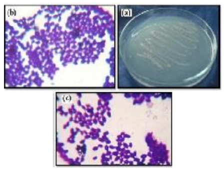
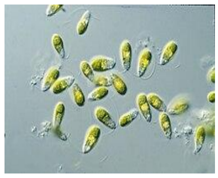
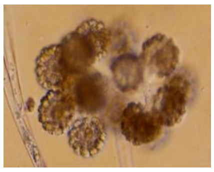
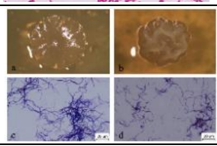
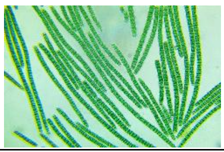
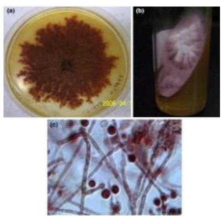
Keywords: Microbial pigments, natural colorants, extraction, fermentation, green technology

Introduction

Growing concern over the environmental and health impacts of synthetic dyes has intensified global interest in sustainable and natural alternatives. Synthetic pigments, despite their extensive application in food, textiles, pharmaceuticals, and cosmetics, are associated with toxicity, carcinogenic potential, and the release of hazardous by-products into ecosystems (Chung, 2016; Zollinger, 2003). These issues have driven researchers and industries to explore safer and more eco-friendly colorants. Among the various sources of natural pigments, microorganisms have emerged as highly promising producers due to their metabolic versatility, rapid growth rates, and independence from climatic conditions (Venil & Ahmad, 2020).

Microbial pigments produced by bacteria, fungi, yeasts, and microalgae are biodegradable, biocompatible, and generally safer than synthetic dyes (Dufossé, 2018) [9]. Unlike plant-derived pigments, microbial pigment production is not constrained by seasonality, land usage, or crop variability, making microbial fermentation a reliable and scalable process (Panesar, Kaur, & Panesar, 2015). Furthermore, many microbial pigments exhibit potent bioactivities, including antioxidant, antimicrobial, anticancer, and immunomodulatory properties, enhancing their value as functional compounds rather than simple colorants (Nigam & Luke, 2016; Dufossé *et al*., 2021) [22]. These bio-functional characteristics expand their applications across various sectors, including nutraceuticals, pharmaceuticals, cosmetics, and biomedicine. Advances in microbial biotechnology, metabolic engineering, and green extraction have significantly improved pigment yields and reduced production costs. Fermentation processes using low-cost substrates, agro-industrial wastes, and optimized culture conditions have further enhanced the economic feasibility of microbial pigment production (Sankari, Hemalatha, & Hemalatha, 2020). Additionally, the shift toward circular bioeconomy models has positioned microbial pigments usustainable as bioproducts that can replace synthetic dyes withot compromising performance or safety.

Table 1: Microorganisms and Their Pigments

Microorganism	Pigment	Chemical Class	Color	Images	References
Rhodotorula spp.	β-Carotene	Carotenoid	Orange		Johnson & Frengova (1998; 2009)
Dunaliella salina	β-Carotene	Carotenoid	Orange		Borowitzka (1988); Ramos *et al*. (2011)
Blakeslea trispora	Lycopene	Carotenoid	Red		Anand & Saxena (2008); Mata-Gómez *et al*. (2014)
Serratia marcescens	Prodigiosin	Tri pyrrole	Red		Haddix *et al*. (2008); Williamson *et al*. (2006)
Chromobacterium violaceum	Violacein	Indole derivative	Violet		Durán & Menck (2001); Choi *et al*. (2015)
Streptomyces spp.	Melanin	Phenolic polymer	Brown to Black		Crawford (1983); Plonka & Grabacka (2006)
Spirulina platensis	Phycocyanin	Phycobiliprotein	Blue		Patel *et al*. (2005); Benedetti *et al*. (2004)
Monascus purpureus	Monascorubrin	Azaphilone	Red/Orange		Dufossé (2006); Blanc *et al*. (1995)

Major classes of microbial pigments

Microorganisms synthesize a diverse range of pigments with significant industrial, pharmaceutical, and biotechnological relevance. These pigments not only impart coloration but also exhibit important bioactivities, making them attractive as natural and sustainable alternatives to synthetic dyes. The major classes of microbial pigments include carotenoids, melanins, violacein, prodigiosin, and phycobiliproteins.

Carotenoids

Carotenoids remain among the most studied microbial pigments. Bacteria are increasingly being recognized as efficient "cell factories" for fundamental carotenoids such as β-carotene, lycopene, zeaxanthin, canthaxanthin, and astaxanthin (Microbial Cell Factories, 2025). These pigments are synthesized via the mevalonate (MVA) or methylerythritol phosphate (MEP) pathways in bacteria, and metabolic engineering (e.g., overexpression of key biosynthetic genes) has shown marked improvements in yields (Microbial Cell Factories, 2025). Functionally, carotenoids exhibit strong antioxidant activity and have been linked to anti-inflammatory and immunomodulatory effects, making them favorable for nutraceutical and pharmaceutical applications (Agarwal *et al*., 2023) [3].

Melanins

Melanins produced by bacteria, fungi, and other microorganisms continue to attract attention due to their physicochemical robustness and biofunctional properties. According to a recent review, bacterial melanins protect against UV radiation and oxidative stress, and they also chelate metal ions (Agarwal *et al*., 2023) [3]. In addition, these pigments demonstrate potential for biotechnological applications spanning cosmetics, environmental remediation (metal-binding), and radioprotection (Neves Junior *et al*., 2023) [21].

Violacein and related pigments
Violacein, a purple pigment predominantly produced by *Chromobacterium violaceum* and *Janthinobacterium lividum*, has been the focus of renewed investigation due to its multifunctional bioactivity. Recent studies show that violacein possesses potent antioxidant capacity (radical scavenging), antimicrobial activity, and even anticancer potential (Agarwal *et al*., 2023; Archives of Pharmacal Research, 2025) [3]. These findings underscore its biotechnological relevance in pharmaceuticals, especially for the development of antimicrobial and therapeutic agents.

Prodigiosin and derivatives
Prodigiosin and related prodiginines remain of high interest. These red Tri pyrrole pigments, produced by organisms like *Serratia marcescens*, have demonstrated an impressive range of bioactivities, including immunosuppressive and anticancer effects (Agarwal *et al*., 2024). Their hydrophobic nature and ability to induce apoptosis in cancer cell lines make prodigiosin-family compounds compelling leads for drug development (Agarwal *et al*., 2023) [3].

Phycobiliproteins
Phycobiliproteins (PBPs) are pigment–protein complexes derived from cyanobacteria and red algae, such as phycocyanin and phycoerythrin. Recent research highlights structural and functional advances: for example, studies on R-phycocyanin from *Porphyra* (nori) species have explored its oligomeric stability under extreme conditions (high pressure), which is relevant for its use in food and biomedical contexts (Minic *et al*., 2024). Phycobiliproteins are valued both as fluorescent markers (in bioimaging and labelling) and as nutraceuticals with antioxidant potential (FPPN, 2023).

Extraction techniques for microbial pigments
Extraction of microbial pigments is a crucial step in downstream bioprocessing because pigments often accumulate intracellularly or are tightly associated with cellular structures. Recent advancements in extraction technologies have focused on increasing yield, reducing solvent usage, and adopting greener, more sustainable methods. Current extraction strategies can be broadly categorized into conventional solvent-based methods, cell-disruption approaches, advanced green extraction techniques, and downstream purification processes.

Conventional methods
Conventional extraction methods for microbial pigments primarily depend on the use of organic solvents such as ethanol, methanol, acetone, and hexane, which effectively solubilize both hydrophobic and hydrophilic pigments (Agarwal *et al*., 2023) [3]. These methods typically involve solvent extraction, maceration to enhance solvent–pigment contact over extended periods, and separation techniques such as centrifugation and filtration to remove microbial biomass and concentrate pigment-rich phases. Despite their widespread use and simplicity, conventional solvent-based techniques possess several limitations, including high solvent consumption, environmental and health-related concerns, and comparatively low extraction efficiency, particularly for intracellular pigments like carotenoids and melanins that require additional cell-disruption steps for effective recovery (Neves Junior *et al*., 2023) [21]. Furthermore, the potential presence of solvent residues may compromise pigment purity and restrict their suitability for sensitive applications in the food, nutraceutical, and pharmaceutical sectors, prompting the need for more efficient and sustainable extraction approaches.

Cell disruption techniques
Since many microbial pigments are located intracellularly, effective cell disruption is essential to release pigments prior to extraction. Recent studies have emphasized the importance of combining cell lysis with solvent extraction to enhance pigment recovery and overall yield (Tang *et al*., 2024) [24]. Cell disruption strategies can be broadly categorized into mechanical and non-mechanical approaches. Mechanical techniques, including bead milling, ultrasonication, and high-pressure homogenization, physically break the microbial cell walls, facilitating the release of intracellular pigments. Ultrasonication, in particular, has gained prominence for its ability to reduce extraction time while increasing yields of pigments such as carotenoids and prodigiosin. Non-mechanical approaches include enzymatic lysis using lysozyme, cellulase, or proteases, osmotic shock, and chemical lysis employing detergents or mild alkali solutions. While enzymatic methods are generally more expensive, they offer high specificity and preserve pigment integrity, making them especially suitable for sensitive pigments embedded within lipid membranes, such as carotenoids (Agarwal *et al*., 2023) [3]. Overall, the combination of appropriate cell disruption techniques with solvent extraction is critical to maximizing the efficiency and quality of microbial pigment recovery.

Advanced and green extraction methods
Traditional pigment extraction methods often rely on organic solvents such as hexane, methanol, or acetone. These solvents can be toxic, flammable, and harmful to the environment if not properly handled or disposed of. Due to growing concerns about environmental pollution, worker safety, and sustainability, researchers are now focusing on advanced and green extraction methods. These techniques aim to reduce solvent use, save energy, and improve pigment yield and quality.
One of the most environmentally friendly techniques is supercritical carbon dioxide (SC-CO_2) extraction. In this method, carbon dioxide is used under high pressure and temperature, allowing it to act as an effective solvent. SC-CO_2 is particularly suitable for extracting nonpolar pigments, such as carotenoids and astaxanthin. It is non-toxic, recyclable, and leaves no solvent residue in the final product. In addition, extraction conditions can be easily adjusted to improve pigment selectivity and purity (Mussagy *et al*., 2021) [20]. Pressurized liquid extraction (PLE) and accelerated solvent extraction (ASE) are modern techniques that use elevated temperature and pressure to improve solvent penetration into microbial cells. These conditions help break down cell walls and release pigments more efficiently. As a result, these methods significantly

reduce extraction time and solvent consumption. They are especially useful for extracting heat-stable pigments, including carotenoids and melanin-based pigments.

Recently, ionic liquids (ILs) and deep eutectic solvents (DES) have gained attention as green alternatives to conventional solvents. These solvents have low volatility, meaning they do not easily evaporate and pollute the air. Their chemical properties can be customized to dissolve specific pigments. Among them, DES are considered safer, cheaper, and more biodegradable, making them suitable for large-scale applications. Studies have shown that DES can efficiently extract hydrophobic pigments while maintaining pigment color and stability (Agarwal *et al*., 2024). Microwave-assisted extraction (MAE) uses microwave energy to heat the moisture inside microbial cells very quickly. This rapid heating causes cell disruption, allowing pigments to escape into the solvent. MAE greatly shortens extraction time and reduces solvent use. It is best suited for pigments that are stable at high temperatures (FPPN, 2023). Another effective technique is ultrasound-assisted extraction (UAE). This method uses high-frequency sound waves to create microscopic bubbles in the extraction solvent. When these bubbles collapse, they generate strong forces that break cell walls and improve solvent movement into the cells. UAE allows efficient pigment extraction with lower energy input and is suitable for both intracellular and extracellular pigments.

Downstream purification

Following extraction, microbial pigments require downstream purification to achieve the high purity necessary for industrial, pharmaceutical, and food applications. Chromatographic techniques, including High-Performance Liquid Chromatography (HPLC) and flash chromatography, are widely employed to separate pigments based on polarity, molecular weight, or charge, and are particularly effective for high-value compounds such as phycobiliproteins, violacein, and carotenoids. Membrane-based filtration methods, such as ultrafiltration and nanofiltration, are used to concentrate pigments and remove residual impurities, making them especially suitable for protein-based pigments like phycocyanin. Crystallization or precipitation is another commonly applied technique, often used for pigments such as prodigiosin and melanin, to obtain purified fractions. Additionally, aqueous two-phase systems (ATPS) provide a gentle and selective separation method for sensitive pigments, utilizing polymer–salt or polymer–polymer systems to partition pigments with minimal degradation (Neves Junior *et al*., 2023) [21]. Collectively, these downstream purification strategies ensure that microbial pigments meet the quality standards required for diverse industrial and biotechnological applications.

Optimization strategies for pigment production

Optimization of microbial pigment production is a multi-pronged strategy that integrates genetic, nutritional, and bioprocess engineering to maximize yield, stability, and cost-efficiency. Key strategies include strain improvement, media and nutrient optimization, fermentation process optimization, and process intensification.

Strain improvement

Strain improvement is a fundamental strategy for enhancing microbial pigment biosynthesis, as pigment yield is strongly influenced by the genetic and metabolic characteristics of the producing organism. Conventional strain improvement techniques, including random mutagenesis induced by ultraviolet (UV) radiation or chemical mutagens such as ethyl methane sulfonate (EMS), have been extensively applied to generate genetic diversity within microbial populations. These approaches facilitate the identification of mutant strains with enhanced pigment-producing capabilities through systematic screening and selection processes (Silva *et al*., 2024). Despite their effectiveness, such methods often require labor-intensive screening due to the random nature of genetic alterations. Adaptive laboratory evolution (ALE) represents an alternative and complementary approach to strain enhancement. In ALE, microorganisms are cultured over extended periods under defined selective pressures, such as nutrient limitation, oxidative stress, or high pigment accumulation. This process promotes the gradual accumulation of beneficial mutations that improve cellular fitness, metabolic robustness, and pigment biosynthetic efficiency, ultimately leading to increased pigment yields.

Recent advances in metabolic engineering and synthetic biology have enabled more precise and rational strain improvement strategies. Genome-editing technologies, particularly CRISPR–Cas systems, allow targeted modification of genes involved in pigment biosynthetic pathways. These modifications include enhancing precursor supply, increasing the activity of rate-limiting enzymes, eliminating competing metabolic pathways, and optimizing transcriptional regulation, thereby significantly improving pigment production efficiency and consistency. Additionally, heterologous expression of pigment biosynthetic pathways in fast-growing and genetically tractable host organisms, such as *Escherichia coli* and yeast, has emerged as a promising strategy for large-scale pigment production. These host systems offer advantages, including rapid growth rates, well-characterized metabolic networks, and ease of genetic manipulation. By transferring pigment biosynthesis genes from native producers into these hosts, high-level and controllable pigment production can be achieved, enhancing industrial scalability and economic feasibility (Agarwal *et al*., 2024; Mussagy *et al*., 2021) [20].

Media and nutrient optimization

The composition of the culture medium plays a crucial role in microbial growth and pigment biosynthesis, as nutrient availability directly influences metabolic pathways and secondary metabolite production. Consequently, media and nutrient optimization have become a key strategy for improving pigment yield and process efficiency. Statistical optimization techniques such as Response Surface Methodology (RSM), Box–Behnken design, and Design of Experiments (DoE) are widely applied to evaluate the individual and interactive effects of multiple variables, including carbon-to-nitrogen (C/N) ratio, precursor concentration, trace elements, pH, temperature, and oxygen availability. These approaches enable systematic optimization with reduced experimental cost and time while providing reliable predictive models for pigment production (Neves Junior *et al*., 2023) [21]. Several studies have reported significant enhancement of pigment yield following media optimization. For instance, optimization of nutrient composition and cultivation conditions has been shown to markedly increase prodigiosin production in *Serratia marcescens*, demonstrating the importance of balanced carbon and nitrogen sources and controlled environmental parameters for efficient pigment biosynthesis (Silva *et al*., 2024).

In addition to defined media optimization, the use of low-cost agro-industrial substrates such as molasses, crude glycerol, fruit peels, and other organic wastes has gained increasing attention. These substrates serve as economical carbon sources, reduce overall production costs, and support sustainable bioprocessing without compromising pigment yield (Agarwal *et al*., 2024). Advanced computational and modeling tools, particularly Artificial Neural Networks (ANNs), have been increasingly applied for predicting optimal nutrient combinations and cultivation conditions. ANNs are capable of modeling complex and non-linear relationships between process variables and pigment production more accurately than conventional statistical methods. Integration of ANN-based predictions with experimental optimization has been shown to further enhance pigment productivity, process robustness, and scalability, highlighting its potential for industrial microbial pigment production (Neves Junior *et al*., 2023) [21].

Fermentation optimization

The selection of appropriate fermentation strategies plays a crucial role in maximizing microbial pigment production. Submerged fermentation (SMF) is widely employed for pigment-producing bacteria and yeasts due to its ease of process control, scalability, and efficient oxygen and nutrient transfer (Mapari *et al*., 2010; Venil *et al*., 2013) [18, 23]. In contrast, solid-state fermentation (SSF) is particularly suitable for filamentous fungi, as it closely mimics their natural growth conditions and often results in higher pigment concentrations with reduced water and energy requirements (Pandey *et al*., 2008; Dufossé, 2018) [9]. Advanced fermentation modes, such as fed-batch and continuous fermentation, are increasingly utilized in bioreactor systems to enhance pigment yields. These approaches allow precise regulation of nutrient availability, oxygen supply, and metabolite accumulation, thereby minimizing substrate inhibition and metabolic stress while promoting sustained pigment biosynthesis (Martínez *et al*., 2019; Tang *et al*., 2024) [19, 24]. The use of bioreactors further enables real-time monitoring and control of critical process parameters, including aeration rate, agitation speed, temperature, pH, and incubation time, all of which significantly influence microbial growth kinetics and pigment production efficiency (Venil *et al*., 2020). Optimization of these physicochemical parameters has been shown to substantially improve pigment productivity, yield consistency, and process reproducibility. Moreover, integrating optimized fermentation conditions with low-cost and renewable substrates, such as agro-industrial residues, significantly enhances the economic feasibility and environmental sustainability of microbial pigment production (Nigam & Luke, 2016; Tang *et al*., 2024) [21, 24]. Collectively, these strategies contribute to the development of cost-effective, scalable, and sustainable fermentation processes for industrial pigment manufacturing.

Process intensification

Process intensification strategies are increasingly employed to enhance pigment productivity while simultaneously reducing operational costs and resource consumption. One widely adopted approach involves the use of immobilized cell systems and biofilm reactors, which enable the maintenance of high microbial cell densities and improve operational stability. These systems allow repeated or prolonged pigment production cycles without the need for frequent reinoculation, thereby reducing downtime and improving overall process efficiency (Agarwal *et al*., 2023) [3]. Co-culture fermentation represents another promising intensification strategy, as it exploits metabolic cooperation between different microbial species. In such systems, one microorganism may synthesize a key precursor compound, which is subsequently converted into the desired pigment by a second strain. This division of metabolic labor can enhance precursor availability, improve conversion efficiency, and ultimately increase pigment yield compared to monoculture fermentations (Neves Junior *et al*., 2023) [21]. Additionally, the application of elicitors, stress factors, or signaling molecules such as oxidative stress, light exposure, nutrient limitation, or quorum-sensing compounds has been shown to activate or upregulate secondary metabolite biosynthetic pathways. These stimuli can trigger enhanced pigment biosynthesis as part of the microbial stress response, leading to increased accumulation of target pigments without genetic modification (Agarwal *et al*., 2023) [3]. Collectively, these process intensification strategies contribute to higher pigment yields, shortened production times, and improved process sustainability. Their integration into industrial fermentation workflows offers significant potential for developing efficient, cost-effective, and environmentally sustainable microbial pigment production systems (Agarwal *et al*., 2023; Neves Junior *et al*., 2023) [3, 21].

Applications of microbial pigments

Microbial pigments possess a wide variety of applications across multiple industries owing to their bioactivity, biodegradability, and functional versatility (Agarwal *et al*., 2023) [3].

Food and beverage industry

In the food industry, microbial pigments serve as natural colorants replacing synthetic dyes such as azo dyes and synthetic carotenes. For instance, carotenoids and *Monascus* pigments are used in beverages, dairy products, and fermented foods (Sen, Barrow & Deshmukh, 2019; Çakmak Sancar *et al*., 2024) [23]. Beyond imparting color, these pigments often provide health benefits: microbial carotenoids act as antioxidants, while antimicrobial pigments can serve as natural preservatives (Sen *et al*., 2019; Heer & Sharma, 2017) [23].

Pharmaceuticals and therapeutics

Microbial pigments like prodigiosin and violacein have demonstrated potent anticancer activity, inducing apoptosis in cancer cells, and thus are explored for anticancer therapeutics (Agarwal *et al*., 2023; Rroij review, 2024) [3]. Carotenoids derived from microbes are also studied for their antioxidant capacity, protecting against oxidative stress-linked diseases (Agarwal *et al*., 2023) [3]. Moreover, many pigments show broad-spectrum antimicrobial and antiviral activity, offering potential as novel therapeutic agents (Rroij review, 2024). Certain pigments are being developed for advanced drug delivery systems and photodynamic therapy because of their biocompatibility and light-responsive properties (Agarwal *et al*., 2023) [3].

Cosmetics

In cosmetics, microbial melanins play a role as UV-protective agents due to their high UV absorption capacity, while carotenoids such as β-carotene and astaxanthin act as natural antioxidants that counter skin aging (Agarwal *et al*., 2023) [3]. Pigments like phycocyanin (from cyanobacteria) and astaxanthin are increasingly being used in skin-care formulations for their dual role as colorants and bioactive antioxidant molecules (Agarwal *et al*., 2023) [3].

Textile and dyeing industry

Microbial pigments offer sustainable alternatives to synthetic dyes in textile industries. Pigments from bacteria and fungi can be used as biodegradable, eco-friendly dyes. Furthermore, biochemical mordants derived from microbial sources can improve the colorfastness of dyed textiles, reducing reliance on harsh chemical mordants (Çakmak Sancar *et al*., 2024; Agarwal *et al*., 2023) [3].

Environmental applications

Some microbial pigments (e.g., melanin) have strong metal-chelating properties and can bind heavy metals for bioremediation of contaminated water or soils (IJSAT, 2025). Pigment-producing microbes have also been explored as biosensors for environmental pollutants, given their pigment production changes in response to toxins (Agarwal *et al*., 2023) [3]. In bioremediation, pigment-producing strains can help degrade pollutants while concurrently producing useful pigment molecules.

Biotechnology and industrial uses

In biotechnology and industrial sectors, microbial pigments have specialized applications. Phycobiliproteins (such as phycocyanin) are widely used as fluorescent markers in imaging and diagnostics (Agarwal *et al*., 2023) [3]. Melanins, due to their conductive and stable polymer-like behavior, are being explored for bioelectronics and bio-material applications (Agarwal *et al*., 2023) [3]. In addition, many microbial pigments have antioxidant properties and can act as natural stabilizers in polymers, preventing oxidative degradation in materials (Agarwal *et al*., 2023) [3].

Sustainability and economic considerations

Microbial pigment production has emerged as a promising sustainable and environmentally friendly alternative to conventional synthetic dyes, primarily due to its significantly lower greenhouse gas emissions and reduced reliance on non-renewable petrochemical resources (Agarwal *et al*., 2023; Dufossé, 2018) [3, 9]. In contrast to chemically synthesized dyes, which often require toxic solvents, harsh reaction conditions, and energy-intensive processing, microbial pigment biosynthesis occurs under mild fermentation conditions, resulting in lower environmental impact and improved process safety (Venil *et al*., 2020; Sen *et al*., 2019) [23]. These attributes strongly align with global sustainability goals and the increasing industrial demand for eco-friendly colorants. The economic feasibility of microbial pigment production is further enhanced through the utilization of renewable and low-cost feedstocks, particularly agro-industrial residues such as fruit peels, molasses, whey, lignocellulosic hydrolysates, and food-processing wastes. The valorization of these substrates not only reduces raw material costs but also contributes to waste management and resource recovery, thereby improving overall process efficiency and sustainability (Neves Junior *et al*., 2023; Nigam & Luke, 2016) [21, 22]. Moreover, the recovery and utilization of microbial by-products—such as enzymes, organic acids, or biomass for animal feed or biofertilizers—can generate additional revenue streams and improve the economic competitiveness of microbial pigment production systems (Martínez *et al*., 2019) [19].

The integration of microbial pigment production into circular bioeconomy and biorefinery frameworks further strengthens its sustainability profile. By coupling pigment biosynthesis with the co-production of other value-added bioproducts, including enzymes, biofuels, bioplastics, and nutraceuticals, it is possible to maximize biomass utilization while minimizing waste generation (Cherubini, 2010; Agarwal *et al*., 2023) [3, 5]. Such integrated approaches enable more efficient use of microbial metabolism and shared infrastructure, leading to reduced operational costs and improved overall process efficiency. These strategies support the transition toward circular industrial systems that emphasize resource efficiency and waste minimization. Several challenges remain that must be addressed to facilitate the large-scale commercialization of microbial pigments. One of the primary limitations is the high cost associated with downstream processing, including pigment extraction, purification, and stabilization, which can account for a significant proportion of total production costs (Venil *et al*., 2020; Tang *et al*., 2024) [24]. Developing scalable, cost-effective, and environmentally benign downstream processing technologies remains a critical area of research. Additionally, ensuring genetic and phenotypic stability of high-yielding microbial strains during prolonged or repeated fermentation cycles is essential to maintain consistent pigment quality and productivity at the industrial scale (Mapari *et al*., 2010; Neves Junior *et al*., 2023) [18, 21].

Regulatory approval represents another major hurdle, particularly for pigments intended for applications in the food, pharmaceutical, and cosmetic industries. Comprehensive safety assessments, toxicological evaluations, and strict quality control measures are required to comply with region-specific regulatory frameworks, such as those imposed by food and drug authorities. These processes are often time-consuming and costly, potentially slowing market adoption (Dufossé *et al*., 2014; Sen *et al*., 2019) [23].

Future perspectives

he future of microbial pigment production is closely associated with rapid advances in synthetic biology and metabolic engineering, which enable the rational design and fine-tuning of biosynthetic pathways to achieve higher pigment yields, improved productivity, and greater structural diversity of color compounds (Agarwal *et al*., 2023; Nielsen & Keasling, 2016) [3, 14]. Tools such as CRISPR-Cas genome editing, pathway modularization, and dynamic regulatory circuits are expected to facilitate precise control over pigment biosynthesis, allowing the development of tailor-made microbial cell factories for specific industrial applications (Keasling, 2010; Venil *et al*., 2020) [14]. In parallel, innovations in bioprocess automation and digitalization are anticipated to significantly enhance

process control, reproducibility, and operational efficiency. The integration of Artificial Intelligence (AI), machine learning, and digital twin technologies into fermentation systems enables real-time monitoring, predictive modeling, and adaptive control of key process parameters, thereby optimizing pigment production while reducing energy consumption and operational costs (Mussagy *et al*., 2021; Camacho *et al*., 2022) [20, 37]. These smart biomanufacturing approaches are particularly valuable for scaling up microbial pigment production and ensuring consistent product quality.
Metabolite-specific fermentation strategies, including dynamic feeding regimes and condition-dependent pathway activation, are expected to facilitate the selective production of target pigments while suppressing unwanted by-products. Such strategies can significantly simplify downstream processing, reduce purification costs, and enhance overall process efficiency (Tang *et al*., 2024; Martínez *et al*., 2019) [19, 24]. Growing consumer awareness and regulatory pressure favoring natural, sustainable, and safe colorants continue to drive industrial interest in microbial pigments across food, cosmetic, textile, and pharmaceutical sectors (Dufossé, 2018; Sen *et al*., 2019) [9, 23]. This increasing demand is accelerating research and commercialization efforts focused on eco-friendly pigment-based products with improved safety profiles and environmental performance. Emerging interdisciplinary applications—such as the integration of microbial pigments with 3D bioprinting, bio-textiles, and functional materials—suggest a transformative role for these biomolecules in next-generation manufacturing systems. These innovations bridge biotechnology with advanced material science and sustainable industrial design, opening new avenues for the development of biodegradable, customizable, and high-value-colored materials (Agarwal *et al*., 2023; Neves Junior *et al*., 2023) [3, 21].

Conclusion

Microbial pigments have emerged as sustainable, versatile, and environmentally benign alternatives to conventional synthetic dyes, offering significant advantages in terms of reduced environmental impact, improved biocompatibility, and renewable production pathways. Recent advances in fermentation optimization, metabolic and synthetic biology, extraction technologies, and downstream purification strategies have substantially improved pigment yields, production efficiency, and product quality, bringing microbial pigments closer to large-scale industrial feasibility. The wide-ranging applications of microbial pigments across diverse sectors, including food and beverages, pharmaceuticals, cosmetics, textiles, and biotechnology, underscore their growing industrial relevance and commercial potential. In addition to their coloring properties, many microbial pigments exhibit functional bioactivities such as antioxidant, antimicrobial, and UV-protective effects, further enhancing their value in high-performance and health-related applications.

The integration of microbial pigment production within circular bioeconomy and biorefinery frameworks, supported by the use of renewable feedstocks and green processing technologies, strengthens their role in sustainable manufacturing systems. Continued innovations in strain engineering, process intensification, and digitalized bioprocess control are expected to address existing challenges related to scalability, cost-effectiveness, and regulatory compliance. By combining functional utility with ecological and economic benefits, microbial pigments are well-positioned to play a transformative role in the future of industrial biotechnology and sustainable bio-based industries. Strategic collaboration between academia, industry, and regulatory bodies will be essential to fully realize their potential and accelerate their adoption as viable alternatives to synthetic colorants.

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