# Chapter 1
# Microbial Production of Bioactive Compounds: Recent Advancements and Trends

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**Abstract** The production of bioactive compounds through microbial sources has gained considerable attention in recent years. The use of microorganisms for producing a wide range of complex molecules with different biological activities for various applications has become increasingly popular. Researchers have recognized a vast number of microorganisms as producers of bioactive compounds with industrial applications. In addition, the use of microorganisms to produce bioactive compounds is considered to be an environmentally friendly and sustainable approach. However, finding the optimal conditions for producing these compounds remains a challenge, and exploring new niches with new microorganisms expands the possibility of discovering novel bioactive compounds. The chapter provides an overview of various applications of bioactive compounds, including food, cosmeceutical/cosmetic products, and environmental and agricultural applications. Overall, this chapter provides valuable insights into the recent advancements and trends in the microbial production of bioactive compounds and identifies the challenges and opportunities for future research in this field.

**Keywords** Bioactive compounds · Pigments · Polysaccharides · Cosmeceuticals

## 1.1 Introduction

Throughout centuries, humans have harnessed the potential of bioactive compounds (BCs) to improve their lives [1]. The scientific community has thoroughly researched BCs, which are characterized by their ability to interact with living tissue

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and cause various biological effects and reactions. Although the exact definition of a BC may be unclear, its influence on biological systems is undeniable [2]. It is widely agreed among authors that these compounds have distinct advantageous qualities that differentiate them from detrimental compounds, like toxic or carcinogenic substances [3, 4].

Recently, there has been a growing interest in using bioactive compounds for various applications, including food, pharmaceuticals, cosmetics, as well as environmental and agricultural applications [3–7].

For instance, in the food industry, BCs serve as additives or can be utilized to create health-promoting products such as food supplements, nutraceuticals, and functional foods [3]. The pharmaceutical industry is researching BCs in order to discover new drugs and therapies, specifically new antibiotics that can combat resistant pathogens [4]. Additionally, BCs are being investigated for the treatment of other disorders such as genetic (cancer), neurological (Alzheimer or Parkinson disease), and metabolic (diabetes and obesity) [8].

As for the cosmetic sector, BCs can be used to formulate skin antiaging, hydrating, whitening, and brightening products. Also, the cosmetic industry is increasingly invested in finding new BCs that provide a range of skin benefits, including protection against UV radiation and treatment of various skin conditions [5, 9]. These compounds can be used in the formulation of various cosmetic products such as moisturizers, antiaging creams, and sunscreens.

When it comes to environmental and agricultural applications, microorganisms have the potential to produce BCs for various applications, including bioremediation, biofertilizers, and biopesticides. Mainly, BCs are being explored for their potential to replace the use of agrochemicals. They can improve the growth, yield, and quality of crops while also reducing the impact on the environment and human health [7].

Certainly, BCs can come from either natural or synthetic sources. In this regard, the worldwide exigencies for natural products have been boosted during the last decade. Furthermore, naturally occurring biological compounds created through microbial cell factories are gaining popularity in both industrial and academic fields [4, 10]. A range of microorganisms, including bacteria, yeast, fungi, and algae, possess the ability to produce a wide assortment of BCs that exhibit diverse biological properties. These BCs have found utility across various industries as well (Fig. 1.1).

The utilization of microbial-produced BCs can provide numerous benefits as compared to other natural sources. One of the major advantages is its higher efficiency, which enables the production of larger amounts of the desired complex molecules. Moreover, the microbial-produced BCs offer greater versatility in terms of the range of molecules that can be produced, making them a more versatile option for various applications. Additionally, the production process is easier to scale, ensuring more efficient and cost-effective production of the desired molecules. Additionally, microbial cell factories can be engineered to consume renewable resources, making them a more sustainable approach to obtaining BCs. Indeed, microbial production of BCs can face many bottlenecks in reaching a commercial

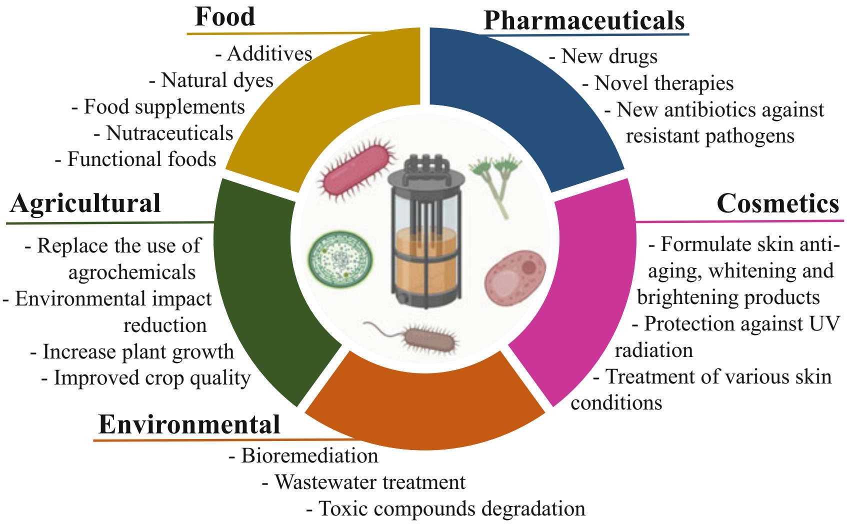

**Fig. 1.1** Applications of microbial bioactive compounds

stage, such as low manufacturing yields, high processing costs, and challenging recovery methods.

This chapter explores the current trend of including bioactive compounds in various industries and explains how microbial production of these compounds is being used in different sectors.

## 1.2 Recent Trends Toward Bioactive Compounds Incorporation into the Market

It has been estimated that the market for bioactive ingredients on a global scale has reached an impressive size of USD $45.5 billion in the year 2022. The projections indicate that this market will continue to grow at a compound annual growth rate (CAGR) of 7.42% from 2022 to 2028, culminating in a forecasted value of USD $69.9 billion by the year 2028 [11]. The fact that there is a growing demand for bioactive ingredients in different industries and their potential to drive innovation and progress is evidenced by this growth. According to the report, the largest segment was food supplements, but personal care and animal nutrition were also included. The report also covered natural BCs extracted from plants.

Regarding the market of microbial products, according to recent projections, the microbial products industry is expected to experience a notable CAGR of 7.6% between 2022 and 2027. This growth is predicted to increase the market's overall value from its current standing of $231.5 billion to $334.2 billion [12]. These numbers indicate significant advancements in this industry and suggest a promising

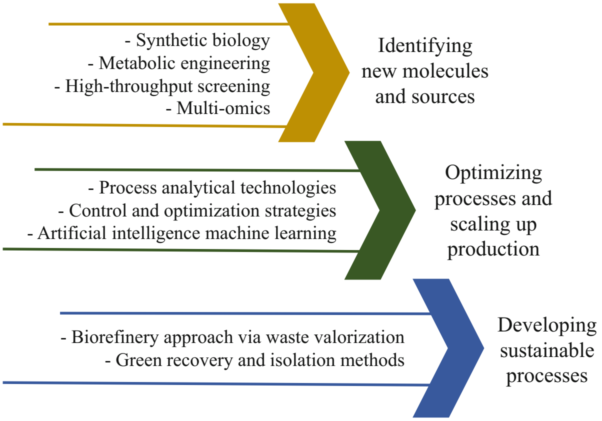

**Fig. 1.2** Recent trends for microbial production of bioactive compounds

future for microbial products. It is worth noting that consumers' increasing awareness of healthy lifestyle choices and their growing demand for products made with natural ingredients are the driving forces behind the growth of both markets. It is crucial to consider these factors when analyzing the market's expansion. On the other hand, the time required to obtain regulatory approval, such as from the FDA, may limit the growth of the microbial BCs market due to high processing costs.

In this regard, the latest trends in microbial-produced compounds aim to enhance process efficiency, improve product quality, reduce costs, and find new sources and compounds. In addition, due to the environmental crisis, both industry and academia have suggested bioprocesses that follow the ideals of cleaner production and a circular economy.

Recent trends in microbial-produced compounds depend on the process stage, whether upstream or downstream, as well as the research and development stage. Therefore, efforts can be targeted toward identifying new molecules and sources, optimizing processes, scaling up production, and developing environmentally friendly recovery methods (Fig. 1.2).

For example, synthetic biology, metabolic engineering, high-throughput screening, and a multi-omics approach have contributed to advancing the development of new microbial cell factories, improving the efficiency of existing ones, and engineering microorganisms to achieve specific objectives [13]. On the other hand, within the processing and scale-up trends, the utilization of process analytical technologies has enabled the application of bioprocess control and optimization strategies to achieve maximum yields and consistency [14, 15]. Artificial intelligence and machine learning are most certainly concepts that have emerged in industrial microbiology to improve the efficiency, consistency, and quality of bioprocesses while reducing the time and cost of developing new bioprocesses [16, 17].

Regarding developing sustainable processes, two main trends are followed, a biorefinery approach for the upstream and a design of a green recovery method for the downstream. In this sense, waste valorization allows converting waste materials into BCs, thus improving economic viability while reducing the amount of waste that ends up contaminating the environment [18, 19]. Meanwhile, green recovery methods enable isolating BCs while reducing the utilization of organic solvents and improving the energy efficiency of the recovery process [20].

Further sections will describe the applications of microbial BCs within distinct sectors and purposes, as shown in Fig. 1.1.

## 1.3 Food Applications and Health Benefits

The extraction and use of secondary BCs in food is a practice that dates back centuries. In ancient Asia, mold-fermented rice was utilized as both a food and traditional medicine [21]. Today, microbial BCs are employed in a variety of food applications, including preservation, color, flavor, texture, and nutritional enhancement, as outlined in Table 1.1.

Lactic acid bacteria (LAB) are a group of bacteria that produce lactic acid as a metabolic product [23]. They are commonly used as starter cultures in the production of fermented foods such as yogurt, cheese, and sauerkraut. Additionally, LAB strains can produce antimicrobial compounds that can serve as natural preservatives in various food products. Juodeikiene et al. [28] employed the extracellular metabolites present in the supernatant broth fermented by LAB to wash off mycotoxins and spores from wheat grains before malting, preventing the undesirable growth of other microorganisms or off-flavors. LAB are recognized not only as an essential group of microorganisms for the dairy industry but also for their catabolic and anabolic metabolism and the benefits that they bring to other fields in the food

**Table 1.1** Applications of bioactive compounds in food and health industry

| Microorganism | Bioactive compound | Activity/Application | References |
|---|---|---|---|
| *Lactobacillus rhamnosus B103* | Lactic acid | Texture and flavor modification in dairy products, meat products preservation. | [22, 23] |
| *Pichia pastoris* | α-Amylases | Starch liquefaction, saccharification, maltose syrup production. | [24] |
| *Talaromyces leycettanus* JCM12802 | Glucoamylases | Starch saccharification, production of high fructose and glucose syrups. | [25] |
| *Saccharomyces cerevisiae* | Glucans | Noncaloric food thickener, fat substitute, emulsifier, foam stabilizer, source of dietary fiber. | [26] |
| *Rhodobacter sphaeroides* HY01 | CoQ10 | Food supplement, energy boosting, antioxidant. | [27] |

industry [22]. Regarding this, the BCs obtained from LAB can be produced either by degradation or synthesis.

LAB have the ability to degrade polysaccharides, providing unique flavors and odors to sourdough, as well as proteins and amino acids, effectively hydrolyzing proteins present in milk and other non-nutritive and harmful substances such as phytic acid or undesirable peptides. Conversely, LAB also produce essential secondary BCs with a significant impact on the food industry, including lactic acid and other organic acids, bacteriocin, vitamins, extracellular polysaccharides, gamma-aminobutyric acid, flavor substances, and antioxidant substances [29].

Filamentous fungi can serve as natural producers of food colorants, with an incredible variety of pigments such as carotenoids, melanins, flavins, phenazines, quinones, monascins, atrorosins, violacein, and indigo [30]. To date, *Monascus* sp. is one of the most extensively studied filamentous fungi, with over 50 different pigments examined. However, *Monascus*-like pigments have also been reported in species of *Talaromyces* and *Penicillium* [31]. Similarly, microbial pigments can also be produced by bacteria. Unlike other microorganism-produced pigments, bacterial pigments have the advantages of a short life cycle and ease of genetic modification. Nevertheless, it is important to note that most bacterial pigments are still in the research and development stage, unlike those produced by fungi.

Enzymes play a crucial role in the food industry, as they can catalyze a wide range of reactions and processes that are important for food production and processing. Raveendran et al. [32] explained the most relevant enzymes and their application, including α-amylase, glucoamylases, proteases, lactase, lipases, phospholipases, esterases, lipoxygenases, cellulases, xylanases, pectinases, glucose oxidase, laccase, catalase, and peroxidase.

Some of the applications of these enzymes are as follows: α-amylase is capable of hydrolyzing glycosidic bonds, resulting in the production of short-chain dextrins. It has a wide range of uses in the baking industry for flavor enhancement, starch liquefaction, brewing, etc.

The major microorganisms used for the industrial production of α-amylase are *Bacillus amyloliquefaciens*, *Bacillus stearothermophilus*, or *Bacillus licheniformis* [33]. Glucoamylases hydrolyze polysaccharide starch, releasing β-glucose. They have major applications in the production of high glucose and fructose syrups, bread quality improvement, and beer production. Glucoamylases are primarily produced by *Aspergillus niger*, *Aspergillus awamori*, and *Rhizopus oryzae*.

Proteases are hydrolytic enzymes that release peptides and amino acids from proteins. They are commonly used for meat tenderization, coagulation of milk, brewing, etc. An important producer of this enzyme due to its low pH tolerance is *Aspergillus usamii* [34]. Lactase is principally used in dairy products to reduce lactose intolerance but is also used as a prebiotic food ingredient. Lactase for industrial use is principally obtained from bacteria like *Bifidobacterium infantis* CCRC 14633, *B. longum* CCRC 15708, *B. longum* CCRC15708, and *Lactobacillus* spp. [35]. For a better understanding of enzyme usage in the food industry, please refer to the work of Raveendran et al. [32].

In addition to enzymes, polysaccharides produced by microbes are also used as food additives to improve the texture of foods. For instance, xanthan gum produced by bacteria such as *Xanthomonas campestris* is used as a thickening agent in foods like salad dressings and sauces [36]. Other examples of microbial polysaccharides, their producers, and applications are glucans from *Saccharomyces cerevisiae*, which can be used as a noncaloric food thickener, gellan from *Pseudomonas elodea*, which is used as a gelling agent, levan from *Alcaligenes viscosus*, which has prebiotic and hypocholesterolemic effects, and emulsan from *Acinetobacter caloaceticus*, which is used as an emulsifying agent [37].

Likewise, microbial BCs are increasingly being recognized for their beneficial properties, which make them attractive for nutritional enhancement and the development of functional foods. These compounds possess various properties such as antioxidants, immune system enhancers, and enzymes that aid in digestion. Carotenoids, for example, are microbial BCs that have been shown to scavenge free radicals and prevent oxidative damage to cells [38], making them potential candidates for preventing chronic diseases such as cancer, diabetes, and cardiovascular disease.

One microbial BC that has gained significant attention in recent years is CoQ10. CoQ10, also known as ubiquinone, is an essential compound that plays a crucial role in the production of ATP, the main energy source for cells. It also acts as an antioxidant, protecting cells from damage caused by free radicals [39]. Although CoQ10 can be found in small amounts in some foods, it can also be produced by microorganisms.

Food supplement products containing CoQ10 produced by microorganisms are available in various forms, such as capsules, tablets, and soft gels. These supplements are marketed as an aid in supporting heart health and improving energy levels. CoQ10 produced by microorganisms has also been added to certain foods, such as beverages, yogurt, and energy bars, to increase their nutritional value. Researchers have explored the potential of purple non-sulfur bacteria (PNSB), a photosynthetic bacterium, for the production of CoQ10. He et al. [40] explained the development and future prospects of CoQ10 production by PNSB. They discussed the possibility of using nontoxic wastewater effluent as a nutrient source for the production of BCs by PNSB, specifically CoQ10. They also explained the bioreactor configuration and important factors that influence the production of CoQ10, such as light, oxygen, and C/N source and ratio. To compensate for the cost of production in their analysis, they must produce 1.4 g/L of biomass and 49.65 mg/g of CoQ10 content. In addition, Zhang et al. [27] demonstrated that a strategy of phosphate limitation along with glucose-fed batch fermentation with the industrial strain *Rhodobacter sphaeroides* HY01 was a positive strategy for CoQ10 production.

Further research is needed to explore the full potential of microbial BCs in food applications and their impact on human health.

## 1.4 Potential Use in Cosmeceutical/Cosmetic Products

Cosmeceutical is a term used to describe a range of products that combine cosmetic and pharmaceutical properties. That is, it describes products that serve cosmetic purposes but also contain active ingredients that may have medicinal or drug-like effects on skin health. These products have become increasingly popular in the marketplace in recent years. The cosmetic industry has shown considerable interest in microbial BCs because of their natural, safe, and effective properties. Additionally, the use of BCs in pharmaceutical/cosmetic fields is of major interest due to their high demand, low required quantity, and high sale price [42]. However, the utilization of BCs entails a rigorous purification and refinement process [43], which may potentially lead to higher processing costs. As previously mentioned, the cost of pure isolated BCs may be too high and could outweigh any benefits. The BCs and their different applications in the cosmeceutical and cosmetic industries are summarized in Table 1.2.

BCs can be utilized as physical agents in cosmetic formulations in order to enhance the stability, thickness, and overall gel-like texture of a diverse array of cosmetic products [52]. For instance, cosmetic products can use microbially produced biosurfactants for diverse functions, including acting as detergents, creating foam, and emulsifying [53].

Moreover, BCs are versatile and can be used in various ways in the cosmetic industry, such as reducing skin aging, brightening the skin, protecting it from UV

**Table 1.2** Applications of bioactive compounds in cosmeceutical/cosmetic industry

| Microorganism | Bioactive compound | Activity/Application | References |
|---|---|---|---|
| *Amorphotheca resinae* | Melanin | Sunscreen, UV protection, antioxidant, antiproliferative effect. | [44] |
| *Serratia marcescens* | Prodiogiosin | Dye, antimicrobial, antiparasitic, anticancer, immunosuppressive effect, sunscreen. | [45] |
| *Nostoc* sp., *LLC-10, Nostoc* sp., *CAQ-15* | Phycobiliproteins | Dye, cosmetic colorant, antioxidant. | [46] |
| *Chromobacterium violaceum* | Violacein | Dye, cosmetic colorant, UV and visible light protection. | [47] |
| *Aspergillus oryzae* | Kojic acid | Skin lightening, UV protection, collagen production. | [48] |
| *Desmodesmus* sp. | Mycosporine-like amino acids (MAAs) | UV protection, sunscreen, antioxidant, anti-inflammatory, antiaging, wound healing. | [49] |
| *Aureobasidium pullulans* | Pullulan | Drug carrier, hydrogels and films for skin hydration, photoprotective, skin whitening, antiaging, sunscreen. | [50] |
| *Streptococcus zooepidemicus* | Hyaluronic acid | Skin moisturizing, sunscreen, dermal fillers, haircare products, nails products. | [51] |

radiation, and treating different skin problems. Specifically, compounds such as microbial pigments have numerous applications in the cosmetic industry due to their ability to impart color but also their beneficial properties, including sunscreen, antioxidants, antiaging agents, and skin lighteners [54]. Some of these pigments include carotenoids, a liposoluble organic pigment that absorbs light energy, thereby helping to prevent sunburn and photoaging. Melanin has antimicrobial, photoprotection, antioxidant, and thermoregulation activities [55]. Phycobiliproteins are colored proteins with antioxidant activity and exhibit red, blue, and green colors [56]. Prodiogiosin is a red pigment with immunosuppressant and anticancer activities, as well as antimicrobial and antimalarial activities [21]. Indigoidine is a water-soluble blue pigment that provides resistance to oxidative stress, and Violacein is a dark-blue pigment that possibly provides protection against UV and visible radiation, as well as antimicrobial effects [57]. The potential of pigments produced by *Talaromyces australis* and *Penicillium murcianum* as a functional cosmetic ingredient was attributed to their antioxidant properties [58]. The authors suggested using ionic gelation for encapsulation as a means to make handling dry powder easier. The method of recovery for microbial pigments holds significant importance due to their comparatively lower stability as compared to synthetic pigments [31]. Furthermore, current trends suggest sustainable and eco-friendly recovery techniques. In this regard, innovative technologies such as ultrasound and alternative solvents such as deep eutectic solvents are being studied [59].

For skin whitening and brightening, kojic acid is a promising compound derived from *Aspergillus oryzae* fermentation [48]. It acts as a natural skin-lightening agent that can help lighten dark spots and brighten the skin by filtering ultraviolet rays, thereby preventing sunburn damage. Kojic acid also inhibits tyrosinase, an enzyme involved in melanin production, making it an effective approach to reducing hyperpigmentation. In addition to its skin-related activities, kojic acid has been found to have antibacterial and antimicrobial properties, making it a potential ingredient for use as a preservative. It also possesses antioxidant activity. Furthermore, kojic acid exhibits a slight anti-inflammatory effect, expanding its range of potential applications [60]. Apart from its cosmetic applications, kojic acid can be used for collagen production, in dental care products, and as a treatment for skin disorders such as melasma and other related diseases [61].

Marine microorganisms, particularly certain strains of cyanobacteria, are capable of producing mycosporine-like amino acids (MAAs), which can absorb UV radiation and are suitable for use in sunscreens and other skincare products [62]. These naturally occurring compounds provide a safe and effective alternative to synthetic UV filters. Microbial carotenoids have also been beneficial for applications to prevent skin damage caused by excessive exposure to ultraviolet radiation [63]. The authors developed nanoemulsions with butiri oil and microbial carotenoids to provide protection against UV rays.

Furthermore, microbial BCs show promise in treating various skin conditions. For instance, *Aureobasidium pullulans*, a fungus that produces pullulan, a natural polysaccharide [64], has demonstrated the ability to improve skin hydration and elasticity and to soothe irritated skin. Hyaluronic acid (HA) is a linear polysaccharide that has become a trend in the cosmetic and cosmeceutical industry. It is widely used due to its water-retention activity, which promotes and maintains skin hydration, making it an excellent ingredient for skin care products [65]. Furthermore, HA has applications beyond esthetics, as it has been proven to be an excellent ingredient for the development of hydrogels to treat xerosis [66].

As previously mentioned, the use of BCs in cosmeceutical products requires highly purified compounds, which can increase production costs. Utilizing waste materials to extract fermentable sugars or to create a fermentation medium is a viable method to reduce costs. This strategy can effectively improve the efficiency of production while also contributing to sustainability efforts. For example, pullulan can be produced by *Aureobasidium pullulans* using soybean meal hydrolysate [41], beta-carotene can be obtained by *Rhodotorula glutinis* using orange and grape wastes [67], and cashew apple juice-based media can be used to produce hyaluronic acid [65]. Furthermore, the incorporation of metabolic pathways into genetically modified strains, such as lignocellulose degradation, has been discussed as a potential opportunity to employ low-cost natural substrates for BCs biosynthesis [68].

The demand for natural and sustainable cosmetic products is increasing, and as a result, the cosmetic industry is expected to use more microbial bioactive compounds in the future.

## 1.5 Environment and Agricultural Applications

One of the current trends in industrial activities is to mitigate the environmental impact caused by the resources required, such as water, energy, and greenhouse gas emissions [69]. Table 1.3 displays various applications of BCs in the environment and agricultural industries.

The main concerns regarding environmental damage are related to heavy metals, petroleum hydrocarbons, synthetic dyes, and the disposal of effluents into land, air, and water bodies [69, 78, 79]. The environmental application of microbial BCs is within the bioremediation field. Bioremediation is a well-established process that involves the use of natural agents to eliminate hazardous pollutants from the environment [70]. Among these agents, microbial bioactive compounds have gained significant attention due to their ability to positively impact the growth and activity of microorganisms involved in biodegradation processes.

Microbial bioactive compounds exert their influence through various mechanisms, including stimulating the growth and activity of indigenous microorganisms and inhibiting the growth of harmful microorganisms. Within the strategies employed to mitigate environmental pollution, microbial platforms have shown the potential to remove contaminants from soil and water effluents [78, 79].

Regarding heavy metal removal, the most commonly cited mechanisms are bioleaching, biosorption, biomineralization, intracellular accumulation, and redox reactions [80]. In line with the proposed focus of this chapter, emphasis should be

**Table 1.3** Applications of bioactive compounds in the environment and agricultural industry

| Microorganism | Bioactive compound | Activity/Application | References |
|---|---|---|---|
| *Phanerochaete chrysosporium* CDBB 686 | Lignin peroxidase, manganese peroxidase, lacase | Biodegradation of synthetic dyes | [70] |
| *Trametes versicolor* | Laccase | Biodegradation of bisphenol A | [71] |
| *Aspergillus melleus* | Lipase | Biodegradation of poly (ε-caprolactone) | [72] |
| *Acinetobacter beijerinckii* | Phytohormones | Enhance soybean plant growth and heavy metal resistance. | [73] |
| *Fusarium oxysporum* | Gibberellic acid | Improve tomato growth and physiological parameters under salt stress | [74] |
| *Paenibacillus polymyxa* KM2501–1 | Volatile organic compounds | Biocontrol of *M. incognita* showing nematicidal, fumigant, and chemotactic activity | [75] |
| *Streptomyces hydrogenans* DH16 | Indole acetic acid | Positive impact on the growth of pea seedlings | [76] |
| *Penicillium oxalicum* | Sanxiapeptin (Aminoacids) | Antimicrobial agent | [77] |

placed on the principle of the bioleaching mechanism, which involves the excretion of organic acids or polymeric substances that cause mineral dissolution [80, 81].

Organic acids such as citric acid, lactic acid, gluconic acid, and oxalic acid are produced in microbial metabolism and interact with surface metal ions to form soluble metal complexes and chelate ions [82]. Bioleaching has been applied in the recovery of metal ions such as, Pb, Ni, Cu, Zn, Al, Ca, P, and Cd from mine tailings, electronic waste, and soil [81–85].

On the other hand, cell wall components of microorganisms have been exploited as bioactive compounds for the biosorption of synthetic dyes or chemical oxygen demand (COD) removal in textile and food industry effluents. Yeast cells of *Saccharomyces cerevisiae*, *Pichia pastoris*, and *Yaworria lipolytica* have shown the potential to remove red, green, blue, and orange colorants [69, 86]. Efficient COD removal of $<50\%$ has been reported in palm oil mill effluent [87], brewery wastewater [88], as well as tannery effluent [89].

Enzymes obtained from microbes or crude enzymatic extracts have been found to be effective for bioremediation [90]. The specific enzyme required for the process depends on the type of pollutant. For example, oxidoreductases can neutralize pollutants that contain free radicals, while hydrolases can assist in the decomposition of organic compounds [91].

Sosa-Martínez et al. [70] demonstrated the possibility of using the crude enzymatic extract produced by *Phanerochaete chrysosporium* CDBB 686 using only agro-industrial waste as a substrate to treat and degrade synthetic pigments in a simulated wastewater system. This approach effectively degraded and lowered the toxicity of the frequently used industrial pigment, methyl green. Even though enzymes are effective in breaking down contaminants, their use in bioremediation remains challenging due to the high costs associated with producing and purifying these biomolecules. Yet, enzymatic processes have significant implications for the management of environmental pollutants, and their potential use in various industries deserves further exploration.

The textile industry provides another example of the potential application of microbial BCs as a substitute for synthetic pigments, thus reducing the industry's impact on the environment. Venil et al. [92] demonstrated the feasibility of using fungal pigments due to their color stability, even withstanding temperature and pH variations when applied to textile fabric. Pigments produced by *Talaromyces amestolkiae* were also used to color latex gloves, replacing synthetic pigments that may cause allergies or generate wastewater effluents [93]. Microalgal by-products have also been studied for their potential application in various industrial fields. Kumar et al. [43] elaborated on the utilization of microalgae for the production of oils that can be efficiently converted into energy. This innovative approach offers a sustainable and eco-friendly alternative to conventional fossil fuel-based energy production methods.

On the other hand, the utilization of microbial BCs for agricultural applications is an emerging field that holds great promise in addressing various agricultural challenges. As mentioned in the introduction, BCs are compounds that can have a positive impact on living organisms, including plants. These compounds have shown to be effective in increasing plant growth and improving crop quality, representing a promising, safer, and more sustainable alternative to agrochemicals.

Fungi, bacteria, and yeast produce metabolites that have a synergic effect on plants to improve growth cycles and crop yields with the minimum environmental harm [94, 95]. In this respect, some mechanisms for promoting plant growth are the solubilization of phosphorous, the production of phytohormones, and the fixation of nitrogen [96].

One of the primary mechanisms by which BCs enhance plant growth is by producing phytohormones. Phytohormones are plant hormones that control specific cellular processes, promoting plant growth and development. While plants do not possess secretion glands, hormones can be located in various sections of the plant and transferred to another location [96, 97]. Nonetheless, fungi are capable of producing some phytohormones that help in the improvement of root and leaf growth [96, 98]. For instance, two of the main hormones produced by microorganisms (*Aspergillus* sp., *Lasiodiplodia theobromae*, *Gibberella fujikuroi*, *Bacillus* sp.) are gibberellic acid and jasmonic acid [98, 99]. Gibberellic acid has been found to increase thermotolerance, growth, biochemical attributes, and yield in various crops, such as tomatoes, lettuce, and chickpeas [100–102]. Such studies have shown that the application of gibberellic acid results in higher crop yields and better crop quality, making it a promising alternative to conventional agrochemicals. Jasmonic acid, on the other hand, has been found to reduce abiotic stress in wheat, cotton, and chickpea plants [103–105].

Furthermore, the production of microbial metabolites is feasible and sustainable due to the utilization of inexpensive substrates [106]. For example, lactic acid bacteria can synthesize B-group vitamins, which can be used to stimulate the growth of several fruits and vegetables as well as obtain a biofortified food crop for human consumption [95].

Microbial BCs have also been proven effective as biocontrol agents. Juveniles of *Meloidogyne incognita* were effectively controlled by the nematicidal activity of volatile organic compounds synthesized by *P. polymyxa* KM2501–1 [75] To find a comprehensive list of fungal biological controls for plant defense, refer to the detailed information review by Sikandar et al. [107].

As more research is conducted in this field, we can expect to see more sustainable and environmentally friendly agricultural practices that rely on microorganisms.

## 1.6 Concluding Remarks: Challenges and Opportunities

The microbial production of bioactive compounds has gained a lot of attention in recent years due to its potential to provide sustainable alternatives to traditional chemical synthesis methods. However, several challenges need to be addressed to enable the widespread adoption of microbial production technologies.

One of the primary challenges is optimizing the production yield and scaling up production to meet commercial demand. Microbial processes' yields can be affected by various factors, including microbial strain, cultivation conditions, and downstream processing. Moreover, the production of bioactive compounds on a large scale might require significant investment for process control, which can be a barrier to entry for small- and medium-sized enterprises.

Another challenge is ensuring the purity and quality of the bioactive compounds produced by microorganisms. Obtaining regulatory approval, particularly from the FDA, can be time consuming and costly, hindering the growth of the microbial BCs market.

If there are unwanted compounds or microorganisms present, it can damage the effectiveness and safety of the final product, which may also hinder their approval. Also, this makes it inappropriate for use in pharmaceuticals, nutraceuticals, food, and other areas. It is of utmost importance to enforce strict quality control measures and analytical methods in order to guarantee the safety and purity of bioactive compounds.

Although there are challenges, the current trends in microbial-produced compounds present numerous opportunities for creating new bioactive compounds. One such opportunity is using genetic engineering techniques to modify microbial strains, which can produce compounds that would be difficult or impossible to synthesize through chemical means.

Moreover, microbial production is an environmentally friendly approach to synthesizing bioactive compounds. This innovative method enables the reduction of harmful solvent use and carbon emissions while promoting a circular bioeconomy through using renewable feedstocks for microbial fermentation. By using waste streams as feedstock, microbial production technologies can help reduce the amount of organic waste sent to landfills and contribute to developing a more sustainable and efficient system. In this sense, the development and adoption of microbial production technologies can contribute to the transition to a more sustainable and circular economy, which is essential to address the environmental, social, and economic challenges of our time.

In conclusion, the microbial production of bioactive compounds offers significant opportunities for developing sustainable and innovative solutions to address various challenges in food, pharmaceutical, cosmetic, agriculture, and other industries. However, continuing research and development will require overcoming the challenges associated with microbial production, such as optimizing yield, maintaining quality and purity, and scaling up production.

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