Advances in Microbiology, 2020, 10, 397-410
https://www.scirp.org/journal/aim
ISSN Online: 2165-3410
ISSN Print: 2165-3402

Biotechnological Potential of Carotenoids Produced by Extremophilic Microorganisms and Application Prospects for the Cosmetics Industry

Tayane de Cássia Dias Mendes-Silva[1*], Rosileide Fontenele da Silva Andrade[2], Marcio Akio Ootani[3], Paulo Vitor Dias Mendes[4], Rafael Artur de Queiroz Cavalcanti de Sá[1], Milena Roberta Freire da Silva[1], Karolayne Silva Souza[1], Maria Tereza dos Santos Correia[1], Márcia Vanusa da Silva[1,5], Maria Betânia Melo de Oliveira[1]

[1]Department of Biochemistry, Federal University of Pernambuco, Recife, Brazil
[2]National Program Postdoctoral CAPES (PNPD), Catholic University of Pernambuco, Recife, Brazil
[3]Bioprocess Laboratory, Center of Strategic Technologies Northeast, Recife, Brazil
[4]Design Department, Federal University of Pernambuco, Recife, Brazil
[5]Nucleus of Bioprospecting and Conservation of the Caatinga, Semiarid National Institute/Ministry of Science, Technology, Innovations and Communications, Campina Grande, Brazil
Email: *tayanecassiamendes@gmail.com

How to cite this paper: de Cássia Dias Mendes-Silva, T., da Silva Andrade, R.F., Ootani, M.A., Mendes, P.V.D., de Queiroz Cavalcanti de Sá, R.A., da Silva, M.R.F., Souza, K.S., dos Santos Correia, M.T., da Silva, M.V. and de Oliveira, M.B.M. (2020) Biotechnological Potential of Carotenoids Produced by Extremophilic Microorganisms and Application Prospects for the Cosmetics Industry. *Advances in Microbiology*, **10**, 397-410.
https://doi.org/10.4236/aim.2020.108029

Received: July 22, 2020
Accepted: August 25, 2020
Published: August 28, 2020

Abstract

Carotenoids are isoprenoid pigments used in food, chemical, textile, pharmaceutical, and cosmetic industries. They act not only as dyes and provitamins A but also have antioxidants, photoprotective, antimicrobial properties, among others. This class of pigment can be obtained traditionally by plants or chemical synthesis, but they have some disadvantages. In recent years, search for alternative sources has been an important strategy for the carotenoid industries. Microbial synthesis is an alternative that has shown good yields, speed, and reduced production costs. Hostile environments, such as the Caatinga domain, represent an interesting source of microorganisms that produce biomolecules, especially carotenoids, because of oxidative stress caused by sunlight. Thus, this region has been attracting the attention of the scientific community and industry for the use of these organisms in the production of carotenoids and applications in cosmetic products; since these compounds have interesting antioxidant and photoprotective properties. In this review, general characteristics of carotenoids, sources of production, industrial applicability, and commercialization will be discussed, as well as perspectives on the production of carotenoids from microorganisms isolated from the Caatinga and their application in anti-UV products.

Keywords

Natural Pigment, Microbial Production, Hostile Environments, Antioxidant, Photoprotection

1. Introduction

The word carotenoid is derived from the scientific name of the carrot *Daucus carote*, identified by Wackenroder in 1831 as the first source of carotene [1]. Carotenoids are one of the classes of natural pigments often found in fruits and vegetables. Also, they are produced by algae, filamentous fungi, yeasts, and bacteria [2] [3]. These pigments are responsible for the colors bright yellow, orange, and red [4].

Most of the commercialized carotenoids are from vegetable extraction and chemical synthesis. Some problems in the production and commercialization of these dyes, such as seasonal and geographical variability, cannot be controlled [5]. On the other hand, chemical synthesis is a generally complex process that causes the formation of hazardous and inappropriate waste when disposed of in the environment; also, this is not considered safe for health [6]. This results in general concern, which reverberates in many discussions about the unwanted effects of these artificial pigments and the future impacts on human health [7] [8].

Therefore, the synthesis of carotenoids by microorganisms is a viable strategy, which meets the safety marketing appeal and makes it possible to obtain these natural pigments on an industrial scale, quickly and efficiently [9] [10]. Unlike traditional production, the microbial pathway for the production of carotenoids does not depend on external factors and on the seasonal supply of raw materials, which allows the generation of vast pigment yields with diverse coloring [3] [10].

Some microorganisms, known as extremophiles, grow in hostile or extreme environments [11]. They are described as potential producers of natural molecules of biotechnological interest. The Caatinga Domain is a very particular habitat with high temperatures, in which the soil can reach 60˚C in periods of drought, thus characterized as an environment of adverse conditions for the growth of microorganisms [12] [13] [14].

Some microorganisms can accumulate carotenoids in response to environmental stress, such as oxidative stress caused by high solar incidence, which contributes to their survival and competitiveness. Although these microorganisms and their ability to synthesize pigments are poorly investigated [15] [16], bioprospection of unknown microorganisms, as a source of new carotenoids, has been highlighted as a focus of research in the biotechnological area [17].

The carotenoids extracted from these organisms stimulate applications in cosmetic products, as they have antioxidant properties, solubility and stability in oil-in-water emulsions, which are attractive for application in sunscreens and other anti-UV products [18] [19], including generating a patente [20]. *β*-carotene, lycopene, and astaxanthin are among the carotenoids described and used as photoprotection due to their antioxidant action, which acts against free radicals induced by UV radiation to protect the skin against erythema [5] [21].

In this context, the present work sought to summarize the characteristics of carotenoids, their structures, properties, classifications, sources of obtention, commercialization, and applications. Besides, this review addresses the production of carotenoids from extremophilic microorganisms, especially from the Caatinga Domain, as a promising source of these biomolecules with interesting properties; as well as, they envision their applications in cosmetic products, especially those with UV protection.

2. Carotenoids

2.1. Molecular Structure

Natural lipophilic pigments, known for their diversity of structures, carotenoids originate from the biosynthetic pathway of terpenoids [22]. These compounds present in their basic structure eight isoprenoid units joined in such a way that the molecule has inverted symmetry in the center. They have linear structures that are, in general, derived from a $C_{40}H_{56}$ acyclic chain with a system of double and single bonds distributed along its length [23].

This system acts as a chromophore and is one of the most striking features of the structure of carotenoids [22]. The length of the chromophore and the presence or absence of functions determine the absorption spectrum. Also, the color of the molecule, besides giving these pigments a high chemical reactivity, can be easily isomerized and oxidized [24] [25].

There were characterized about 500 structures. More than 95% of carotenoids are formed by a chain of 40 carbons, which is known as tetraterpenoids. Also, there are groups formed by 30 and 50 carbon atoms [26] [27].

From this diversity of structures, carotenoids naturally have different physical, chemical, functional properties, and even stability [25]. Some of these properties were described by these authors are shown in **Figure 1**.

2.2. Classification and Diversity of Carotenoids

Carotenoids are classified into two large groups according to the characteristics of their molecular structures:

- Carotenes: molecular formula $C_{40}H_{56}$, which include *α*, *β*, *γ*-carotenes, and lycopene;
- Xanthophylls: oxygenated and hydroxylated derivatives of carotenes, which include cryptoxanthin ($C_{40}H_{55}OH$) and lutein ($C_{40}H_{54}(OH)_2$).

This classification occurs according to the absence or presence of oxygen atoms [28].

Carotenes are characterized by its composition, only of carbon and hydrogen (pure hydrocarbons), which can be cyclized at one or both molecule extremities, while xanthophylls are oxygen-substituting groups, (hydroxy, methoxy, carboxy, keto and epoxy groups) that generate many structural derivatives and higher polarity when compared to carotenes (**Figure 2**) [29] [30] [31].

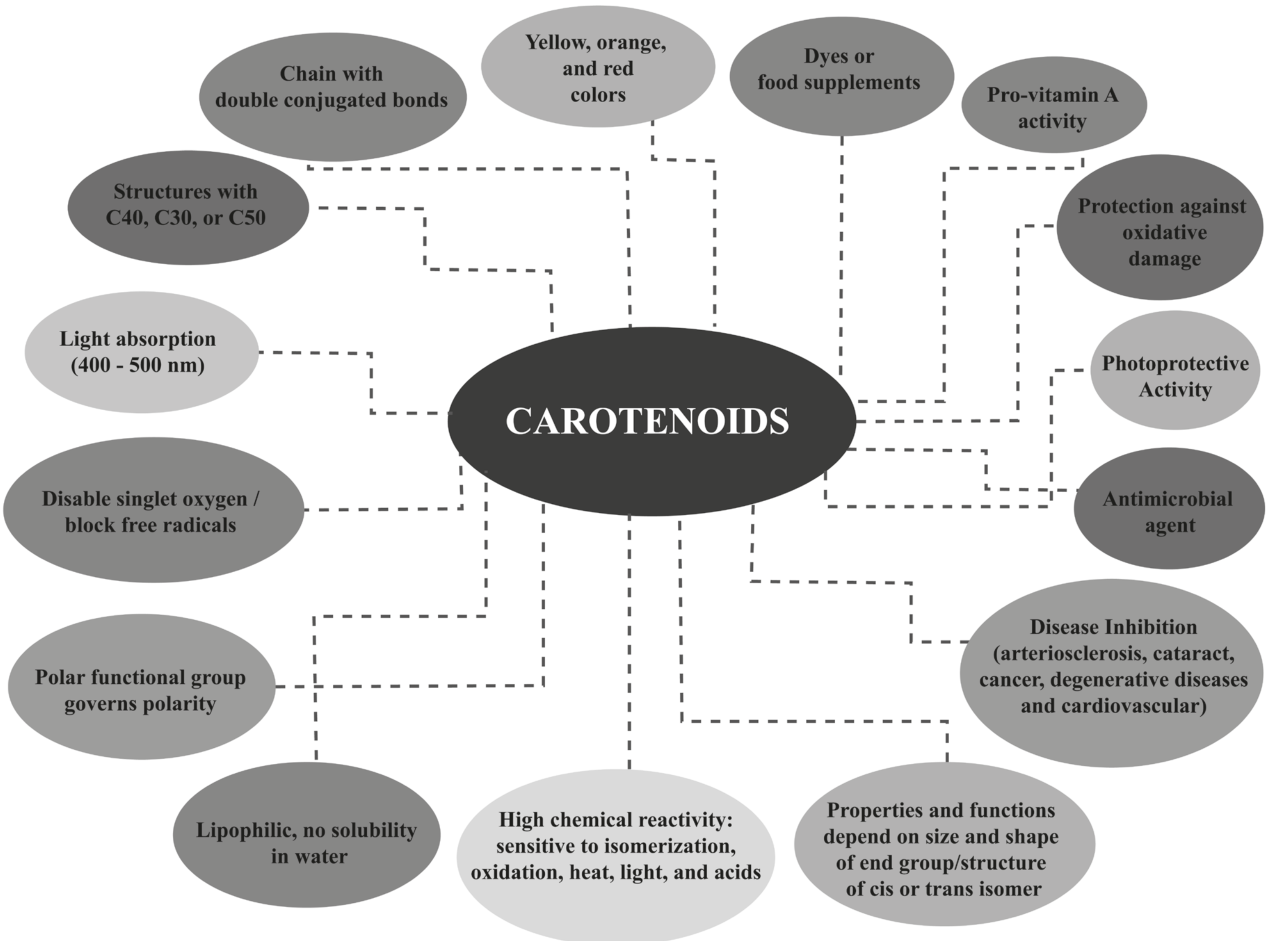

Figure 1. Physical, chemical, and biological properties of carotenoids. Source: Kirti *et al.* [25] with adaptations.

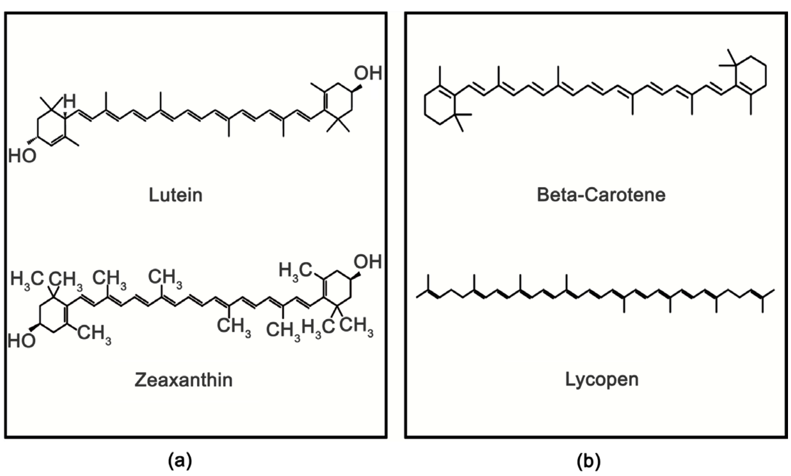

Figure 2. Structure of the carotenoids: (a) xanthophylls; (b) Carotenes. Source: Valduga *et al.* [6] with adaptations.

Isomerization and oxidation of trans carotenoids (stable form in nature) to the cis form (loss of color and activity) can occur with the modification of the basic acyclic structure C40 by hydrogenation, dehydrogenation, cyclization or oxidation, generating great variability of carotenoids [31] [32] [33] [34]. The most commonly found in nature and food are β-carotene, α-carotene, β-cryptoxanthin, lycopene, lutein, violaxanthin, and zeaxanthin; due to this availability, they are the most studied in terms of biological activities that help in health promotion [35].

3. Application and Commercialization of Carotenoids in Industrial Products

Commercial production of carotenoids has been developed, since 1954. They have been, since then, used as a food coloring and nutritional supplements. Also, they help to maintain the aromas and vitamins of foods [36]. Besides, they are used in the production of margarine and butter, fruit juices and drinks, soups, dairy products, as well as in fish, desserts, sugar, salad dressings, meats, pasta, eggs, and mayonnaise industries [37] [37]. These biomolecules are also added in animal feed, in aquaculture, for example, they are sources of pigmentation for fish and crustaceans [34] [39]. This sector of animal feed is the sector with the highest growth, and it is estimated that it will comprise the largest carotenoid market in 2023, according to the Global Carotenoid Market [5].

Carotenoids can be used in various ways in the pharmaceutical and medical industry, such as pro-biotic, syrups, antimicrobial agents, for controlling diseases, and in the modulation of immunological reactions. For environmental purposes, they are used as bioindicators, as well as they are applied in the cosmetics industry for the production of protectors, tanners, creams, among other products [37] [38].

According to Cutzu *et al.* [40], the total value of carotenoids in the global market has an annual growth of 2.3%. According to BCC [41], in 2017, it was expected to reach $1.5 billion, and forecasts for 2022 will be $2.0 billion. In the period between 2007 and 2017, the value increased twice, since the estimated global scale value in 2007 was 766 million dollars. This growth, in the market, has been driven by the properties of carotenoids, global megatrend of the amplification of carotenoids use, demand for applications, and growing interest in developing processes to efficiently produce these pigments [5] [40].

Initially and until 2016, the global manufacturing industry for this group of dyes was dominated by suppliers from Europe, such as the United Kingdom, Switzerland, Germany, France, Italy, the Netherlands, and Spain. However, in recent years, the Asia-Pacific region has been growing and receiving investments and research initiatives for the use of carotenoids [17]. The main industrial producers identified in the global carotenoid market are BASF SE (Germany), Hoffmann-La Roche (Switzerland), Royal DSM NV (Netherlands), Chr. Hansen A/S (Denmark), FMC Corporation (USA), Kemin Industries, Inc. (USA), and Cyanotech Corporation (USA) [5]. They produce and commercialize different carotenoids such as β-carotene, canthaxanthin, astaxanthin, apocarotenoids, and citranaxanthin [24] [42].

4. Microbiological Production of Carotenoids

Due to the global demand for natural dyes, there is an increasing preference for pigments of microbial origin, and being produced for the food industry, textile dyeing, pharmaceuticals, and cosmetics [17]. This search has resulted in constant research regarding the production of microbial carotenoids in biotechnological processes [36] [43] [44]. Carotenoids are synthesized by some bacteria, filamentous fungi, yeasts, and microalgae, which have few commercially exploited species [2] [25] [45].

Production of carotenoids by microorganisms demonstrates a safe use. Also, it has been an area of intense investigation since it allows the obtaining of the compounds of natural origin on an industrial scale, which is being considered a promising production strategy [25] [43].

This type of production has some advantages, as it is a fast, highly efficient process that can be easily managed during production. At the same time, it is superior in versatility and productivity and is independent of climatic conditions when compared to production from fruits and vegetables [3] [46]. Finally, it is possible to produce different shades of color with a relatively easy procedure for extracting and separating cell biomass. Also, the microorganisms can grow on cheap substrates [10] [25].

To further increase yields and guarantee the production of microbial carotenoids, studies have been carried out on processes to optimizing cultivation conditions, the use of cheap substrates, and genetic engineering studies [3] [17].

Despite the large number of microbial carotenoids already identified and characterized, only a few are produced on an industrial scale. Also, the market for carotenoids synthesized by bioprocesses is still a little difficult to estimate. It is due to the lack of statistics on regional low-tech products or because production is dispersed in small companies around the world.

Among the products already available on the market obtained through microbially, there is astaxanthin produced by the yeast *Phaffia rhodozyma*, the bacterium *Agrobacterium auranticum*, and the freshwater microalgae *Haematococcus pluvialis* [25] [47], also β-carotene synthesized by *Blakeslea trispora* and zeaxanthin produced by *Flavobacterium*. It also stands out the production of β-carotene, torulene, and torularodine by yeasts of the genus *Rhodotorula* [25] [47]. Besides, these microbial pigments are considered safe and approved by the Food and Drug Administration (FDA) [17].

Much research is been directed to find new sources of this group of pigments, which has promising properties, and strategies that can increase the efficiency of these biotechnological systems. So, these dyes are commercially viable and can be expanded in the various industrial sectors [40] [48].

5. Biotechnological Potential of the Caatinga Domain

The Caatinga domain has the most extreme meteorological values in Brazil. It has the strongest sunshine, the lowest cloudiness, low annual precipitation rates (below 800 mm), and high daytime temperatures, which can vary between 23˚C and 27˚C, while the soil can reach temperatures close to 60˚C [12] [14].

This region is of fundamental importance in the life of local communities. It offers a wide variety of plants that are used for medicinal purposes, and that explicit the potential of this domain for research studies of new bioactive products [49] [50] [51] [52].

Among the compounds produced by some plants in the Caatinga and identified by their beneficial biological actions to health, there are carotenoids. In a study by David *et al.* [53], there was possible to correlate the antioxidant and cytotoxic activity with the presence of β-carotenes in Caatinga plants. The greatest activities were observed in *Passiflora cincinnata*, *Chamaecrista repens*, *Rollinia leptopetala*, *Serjania glabrata*, *Diospyros gaultheriifolia*, and *Mimosa ophtalmocentra*.

Another source of carotenoids in the Caatinga is carotenogenic microorganisms, but little is known about them since most studies describe the carotenoids synthesized by plants, as well as their respective biological activities. In a group of bacteria, for example, the information obtained is that only 1% of bacteria in this domain (including pigmented and non-pigmented ones) have already been discovered and described [54]. However, after the publication of this percentage, referring to groups of microorganisms in the Caatinga Domain and their carotenogenic potentials, there is a scarcity of these data in literature over the years.

Thus, as it constitutes an environment with interesting biotechnological potential and with little information in the field of microbial bioprospecting, greater attention is needed to the Caatinga and the development of more studies [55]; since, it presents a vast diversity of microorganisms, little explored and in which new natural carotenoid producers can be discovered.

Microorganisms Isolated from the Caatinga Domain as New Sources of Carotenoids

Microorganisms isolated from environments that present extreme conditions are considered hostile or extreme [56]. To guarantee their survival, they develop biochemical mechanisms and produce metabolites to overcome these unfavorable factors. An example of this efficient strategy is the synthesis of carotenoid pigments to minimize the effects of oxidative damage on cells and other damage caused by high sun exposure [3] [15] [16].

The soil of these arid or semi-arid environments, considered as a hostile or extreme environment, is recognized as a rich habitat. It has microorganisms that produce natural molecules with biotechnological potential, whose biological activities are extremely rich and still poorly explored [55] [57] [58].

Microorganisms most found in the soil microbiota of this environment belong to the phylum Actinobacteria, which perform essential functions for the ecological balance of this habitat [59]. This group grows in extreme conditions, such as soils with low moisture content, typical of semi-arid regions, as well as being representative in terms of richness and diversity [11] [58]. They produce pigments of different colors such as carotenoids, which characterize the group and contribute to environmental resistance. They also produce extracellular enzymes and important secondary metabolites [55] [60].

In a study by Ramos *et al.* [15], the pigment production and chromogenic diversity of soil actinobacteria from the semiarid region of Ceará state were evaluated. It classifies some strains according to color. Also, it suggests the presence of some genera described in the literature as carotenoid producers; characterized by a yellow color, the genera *Actinoplanes*, *Agrococcus*, *Arsenicicoccus*, *Cellulomonas*, *Kocuria*, *Microbacterium*, *Rhodococcus*, *Serinicoccus*, *Streptomyces* were found, and as representatives of the pink color *Arthrobacter* and *Gordonia*. It can be seen among these genera, that the majority was responsible for the production of yellow carotenoids. According to Kampe *et al.* [61] and Kavamura *et al.* [62], this color is characteristic of a microbiota specialized in biomolecules with photoprotective properties. Also, they have structures that contribute to these properties.

As actinobacteria, the presence of some yeasts in the microbiota of these hostile Brazilian environments also stands out. Da Silva Andrade *et al.* [63], showed that from the yeast, *Rhodotorula glutinis*, isolated at the semi-arid Pernambucano soil, *β*-carotene can be obtained by using economical production conditions. Also, the ability of this carotenoid to inhibit cell growth of tumor cells was evaluated and effective for breast cancer and promyelocytic leukemia.

These data corroborate with the idea that the Caatinga Domain is a potential source of microorganisms that produce promising molecules, especially carotenoids. Also, it will be a region of great interest to biotechnologists, which has prospects for applications in industries.

6. Application of Carotenoids in the Cosmetics Industry

Chemical UV filters do not fully protect the skin, as they absorb, instead of reflecting or spreading all the UV photons that reach the skin. Most of the consequences caused by UVA radiation are related to the generation of Reactive Oxygen Species (ROS) after exposure. Therefore, it is necessary to add antioxidant molecules to sunscreens, especially in topical products, which minimize UV damage to the skin [64].

Carotenoids have aroused the interest of the cosmetic industries, since they are important natural antioxidants acting in the reduction of the generation of free radicals and, consequently, diminish the photodamage in the skin [65]. Also, they have a promising anti-UV capability, which boosts the development of photoprotective cosmetic formulations [3]. Whereas, it is intended to reduce the concentration of chemical filters or replace them with sunscreens based on natural products [26].

β-carotene, lycopene, and astaxanthin are among the most described carotenoids and used as photo protectors since they have strong antioxidant properties [21]. *β*-carotene, known as a precursor to provitamin A, a strong inhibitor of $^1O_2$, and free radical scavenger is strongly associated with its accumulation in the skin after ingestion, and later, its transformation into vitamin A in the body, which helps in the formation of melanin [66].

Lycopene, a potent antioxidant, has a significant correlation in skin roughness. It suggests that higher levels of skin antioxidants effectively can reduce skin roughness [66] [67]. Astaxanthin acts as an effective antioxidant against lipid peroxidation and oxidative stress. Also, this property is associated with the prevention of the formation of spots and wrinkles on human skin [66].

However, the application of these carotenoids at the topical level is still poorly investigated; they are normally produced commercially for oral use. Studies with cosmetics formulations, which use these molecules, demonstrate interesting results as far as oral ingestion, reinforcing the approach of using topical carotenoids to prevent oxidative stress induced by acute UV exposure. Also, it supplies cutaneous levels of antioxidants, among other benefits [66] [68].

Carotenoids extracted from microorganisms have been stimulating their applications in formulations of sunscreens and other anti-UV products since they have powerful antioxidant properties, solubility, and stability in oil emulsions. Rare carotenoids with excellent properties can be isolated as well as the carotenoids used traditionally [19], which makes them attractive even for the production of patents [20].

In this context, due to the extreme conditions described above, the microorganisms isolated from the Caatinga Domain present themselves as promising sources of carotenoids little studied, which stimulates their use in cosmetic products. Also, the production of these molecules is induced by strong UV exposure, which demonstrates interesting antioxidant and photoprotective properties.

Thus, as future perspectives, bioprospecting research in the Caatinga should be strongly encouraged. It will allow an increase in the number of natural resources of carotenoids, and even investigate those considered rare and poorly described. Therefore, based on these data, actions and strategies for the economic use of these molecules can be defined, with the generation of biotechnological products with applications both in the cosmetics industry and in other industrial sectors; through its technology without harming the natural relationships of the environment and preserving its biodiversity [69].

Acknowledgements

The authors are grateful for the financial support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior ou Educação (CAPES).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Kaczor, A., Barańska, M. and Czamara, K. (2016) Carotenoids: Overview of Nomenclature, Structures, Occurrence and Functions. In: Kaczor, A. and Baranska, M., Eds., *Carotenoids*: *Nutrition*, *Analysis and Technology*, John Wiley & Sons, Ltd., Hoboken, 1-13. https://doi.org/10.1002/9781118622223.ch1

[2] Carle, R. and Schweiggert, R. (2016) Handbook on Natural Pigments in Food and Beverages: Industrial Applications for Improving Food Color. Woodhead Publishing, Sawston.

[3] Ram, S., Mitra, M., Shah, F., Tirkey, S.R. and Mishra, S. (2020) Bacteria as an Alternate Biofactory for Carotenoid Production: A Review of Its Applications, Opportunities and Challenges. *Journal of Functional Foods*, **67**, Article ID: 103867. https://doi.org/10.1016/j.jff.2020.103867

[4] Wang, N., Manabe, Y., Sugawara, T., Paul, N.A. and Zhao, J. (2018) Identification and Biological Activities of Carotenoids from the Freshwater Alga *Oedogonium intermedium*. *Food Chemistry*, **242**, 247-255. https://doi.org/10.1016/j.foodchem.2017.09.075

[5] Bogacz-Radomska, L., Harasym, J. and Piwowar, A. (2020) Commercialization Aspects of Carotenoids. In: Galanakis, C.K., Ed., *Carotenoids*: *Properties*, *Processing and Applications*, Elsevier, Amsterdam, 327-357. https://doi.org/10.1016/B978-0-12-817067-0.00010-5

[6] Valduga, E., Tatsch, P.O., Tiggemann, L., Treichel, H., Toniazzo, G., Zeni, J., Di Luccio, M. and Furigo, A. (2009) Produção de carotenoides: Microrganismos como fonte de pigmentos naturais. *Química Nova*, **32**, 2429-2436. https://doi.org/10.1590/S0100-40422009000900036

[7] Ribeiro, J.E.S., Da Silva Sant'Ana, A.M., Martini, M., Sorce, C., Andreucci, A., De Melo, D.J.N. and Da Silva, F.L.H. (2019) *Rhodotorula glutinis* Cultivation on Cassava Wastewater for Carotenoids and Fatty Acids Generation. *Biocatalysis and Agricultural Biotechnology*, **22**, Article ID: 101419. https://doi.org/10.1016/j.bcab.2019.101419

[8] Mussagy, C.U., Winterburn, J., Santos-Ebinuma, V.C. and Pereira, J.F.B. (2019) Production and Extraction of Carotenoids Produced by Microorganisms. *Applied Microbiology and Biotechnology*, **103**, 1095-1114. https://doi.org/10.1007/s00253-018-9557-5

[9] Torregrosa-Crespo, J., Montero, Z., Fuentes, J.L., Reig García-Galbis, M., Garbayo, I., Vílchez, C. and Martínez-Espinosa, R.M. (2018) Exploring the Valuable Carotenoids for the Large-Scale Production by Marine Microorganisms. *Marine Drugs*, **16**, 203. https://doi.org/10.3390/md16060203

[10] Malik, K., Tokkas, J. and Goyal, S. (2012) Microbial Pigments: A Review. *International Journal of Microbial Resource Technology*, **1**, 361-365.

[11] Canganella, F. and Wiegel, J. (2011) Extremophiles: From Abyssal to Terrestrial Ecosystems and Possibly beyond. *Naturwissenschaften*, **98**, 253-279. https://doi.org/10.1007/s00114-011-0775-2

[12] Apgaua, D.M.G., Dos Santos, R.M., Pereira, D.G.S., De Oliveira Menino, G.C., Pires, G.G., Fontes, M.A.L. and Tng, D.Y.P. (2014) Beta-Diversity in Seasonally Dry Tropical Forests (SDTF) in the Caatinga Biogeographic Domain, Brazil, and Its Implications for Conservation. *Biodiversity and Conservation*, **23**, 217-232. https://doi.org/10.1007/s10531-013-0599-9

[13] Souto, P.C., Souto, J.S., Santos, R.V.D., Bakke, I.A., Sales, F.D.C.V. and Souza, B.V.D. (2013) Taxa de decomposição da serapilheira e atividade microbiana em área de Caatinga. *Cerne*, **19**, 559-565. https://doi.org/10.1590/S0104-77602013000400005

[14] Menezes, K.A.S., De Oliveira Nunes, G.F., Sampaio, A.A., De Tarso Aidar, S., Martins, L.M.V. and Fernandes-Júnior, P.I. (2015) Seedling Development of Nodulating and Non-Nodulating Native Legumes in Soils from Brazilian Caatinga Biome. *Plant Science Today*, **2**, 56-59. https://doi.org/10.14719/pst.2015.2.2.97

[15] Ramos, K.A., De Brito, F.A.E., Janielle, K., Nunes, F., Martins, C.M. and Martins, S.C.S. (2015) Caracterização e diversidade cromogênica de actinobactérias de um nicho microbiano preservado no bioma Caatinga. *Enciclopédia Biosfera*, **11**, 2115-2125.

[16] Sharma, M., Dangi, P. and Choudhary, M. (2014) Actinomycetes: Source, Identification, and Their Applications. *International Journal of Current Microbiology and Applied Sciences*, **3**, 801-832.

[17] Venil, C.K., Zakaria, Z.A. and Ahmad, W.A. (2013) Bacterial Pigments and Their Applications. *Process Biochemistry*, **48**, 1065-1079. https://doi.org/10.1016/j.procbio.2013.06.006

[18] Martins, A., Tenreiro, T., Andrade, G., Gadanho, M., Chaves, S., Abrantes, M., Calado, P., Tenreiro, R. and Vieira, H. (2013) Photoprotective Bioactivity Present in a Unique Marine Bacteria Collection from Portuguese Deep Sea Hydrothermal Vents. *Marine Drugs*, **11**, 1506-1523. https://doi.org/10.3390/md11051506

[19] Netzer, R., Stafsnes, M.H., Andreassen, T., Goksøyr, A., Bruheim, P. and Brautaset, T. (2010) Biosynthetic Pathway for γ-Cyclic Sarcinaxanthin in *Micrococcus luteus*: Heterologous Expression and Evidence for Diverse and Multiple Catalytic Functions of C_{50} Carotenoid Cyclases. *Journal of Bacteriology*, **192**, 5688-5699. https://doi.org/10.1128/JB.00724-10

[20] Goksøyr, A. (2013) Carotenoid Sunscreen. Google Patents.

[21] Stahl, W. and Sies, H. (2012) β-Carotene and Other Carotenoids in Protection from Sunlight. *The American Journal of Clinical Nutrition*, **96**, 1179S-1184S. https://doi.org/10.3945/ajcn.112.034819

[22] Rodriguez-Amaya, D.B. (2019) Update on Natural Food Pigments-A Mini-Review on Carotenoids, Anthocyanins, and Betalains. *Food Research International*, **124**, 200-205. https://doi.org/10.1016/j.foodres.2018.05.028

[23] Aryee, A.N., Agyei, D. and Akanbi, T.O. (2018) Recovery and Utilization of Seaweed Pigments in Food Processing. *Current Opinion in Food Science*, **19**, 113-119. https://doi.org/10.1016/j.cofs.2018.03.013

[24] Britton, G. (1995) Structure and Properties of Carotenoids in Relation to Function. *The FASEB Journal*, **9**, 1551-1558. https://doi.org/10.1096/fasebj.9.15.8529834

[25] Kirti, K., Amita, S., Priti, S., Kumar, A.M. and Jyoti, S. (2014) Colorful World of Microbes: Carotenoids and Their Applications. *Advances in Biology*, **2014**, Article ID: 837891. https://doi.org/10.1155/2014/837891

[26] Heider, S.A., Peters-Wendisch, P., Wendisch, V.F., Beekwilder, J., Brautaset, T. (2014) Metabolic Engineering for the Microbial Production of Carotenoids and Related Products with a Focus on the Rare C_{50} Carotenoids. *Applied Microbiology and Biotechnology*, **98**, 4355-4368. https://doi.org/10.1007/s00253-014-5693-8

[27] Rodriguez-Amaya, D.B. (2015) Food Carotenoids: Chemistry, Biology and Technology. John Wiley & Sons, Hoboken. https://doi.org/10.1002/9781118864364

[28] Amorim-Carrilho, K., Cepeda, A., Fente, C. and Regal, P. (2014) Review of Methods for Analysis of Carotenoids. *TrAC Trends in Analytical Chemistry*, **56**, 49-73. https://doi.org/10.1016/j.trac.2013.12.011

[29] Botella-Pavía, P. and Rodríguez-Concepción, M. (2006) Carotenoid Biotechnology in Plants for Nutritionally Improved Foods. *Physiologia Plantarum*, **126**, 369-381. https://doi.org/10.1111/j.1399-3054.2006.00632.x

[30] Moliné, M., Libkind, D. and Van Broock, M. (2012) Production of Torularhodin, Torulene, and β-Carotene by *Rhodotorula Yeasts*. In: Barredo, J.L., Ed., *Microbial Carotenoids from fungi*, Humana Press, Totowa, 275-283. https://doi.org/10.1007/978-1-61779-918-1_19

[31] Ngamwonglumlert, L., Devahastin, S. and Chiewchan, N. (2017) Natural Colorants: Pigment Stability and Extraction Yield Enhancement via Utilization of Appropriate Pretreatment and Extraction Methods. *Critical Reviews in Food Science and Nutrition*, **57**, 3243-3259. https://doi.org/10.1080/10408398.2015.1109498

[32] Gomes, F.D.S. (2007) Carotenóides: Uma possível proteção contra o desenvolvimento de câncer. *Revista de Nutrição*, **20**, 537-548. https://doi.org/10.1590/S1415-52732007000500009

[33] Provesi, J.G. and Amante, E.R. (2015) Carotenoids in Pumpkin and Impact of Processing Treatments and Storage. In: Preedy, V., Ed., *Processing and Impact on Active Components in Food*, Elsevier, Amsterdam, 71-80. https://doi.org/10.1016/B978-0-12-404699-3.00009-3

[34] Schroeder, W.A. and Johnson, E.A. (1995) Singlet Oxygen and Peroxyl Radicals Regulate Carotenoid Biosynthesis in *Phaffia rhodozyma*. *Journal of Biological Chemistry*, **270**, 18374-18379. https://doi.org/10.1074/jbc.270.31.18374

[35] Yang, M., Wang, Y., Liu, Q., Liu, Z., Jiang, F., Wang, H., Guo, X., Zhang, J. and Kang, L. (2019) A β-Carotene-Binding Protein Carrying a Red Pigment Regulates Body-Color Transition between Green and Black in Locusts. *eLife*, **8**, e41362. https://doi.org/10.7554/eLife.41362

[36] Marova, I., Haronikova, A., Petrik, S., Dvorakova, T. and Breierova, E. (2012) Production of Enriched Biomass by Red Yeasts of *Sporobolomyces* sp. Grown on Waste Substrates. *The Journal of Microbiology, Biotechnology and Food Sciences*, **1**, 534.

[37] El-Banna, A.A., El-Razek, A.M.A. and El-Mahdy, A.R. (2012) Some Factors Affecting the Production of Carotenoids by *Rhodotorula glutinis* var. *glutinis*. *Food and Nutrition Sciences*, **3**, 64-71. https://doi.org/10.4236/fns.2012.31011

[38] Latha, B. and Jeevaratanm, K. (2012) Thirteen-Week Oral Toxicity Study of Carotenoid Pigment from *Rhodotorula glutinis* DFR-PDY in Rats. *Indian Journal of Experimental Biology*, **50**, 645-651.

[39] Aksu, Z. and Eren, A.T. (2007) Production of Carotenoids by the Isolated Yeast of *Rhodotorula glutinis*. *Biochemical Engineering Journal*, **35**, 107-113. https://doi.org/10.1016/j.bej.2007.01.004

[40] Cutzu, R., Coi, A., Rosso, F., Bardi, L., Ciani, M., Budroni, M., Zara, G., Zara, S. and Mannazzu, I. (2013) from Crude Glycerol to Carotenoids by Using a *Rhodotorula glutinis* Mutant. *World Journal of Microbiology and Biotechnology*, **29**, 1009-1017. https://doi.org/10.1007/s11274-013-1264-x

[41] BCC Research (2018) The Global Market for Carotenoids. https://www.bccresearch.com/market-research/food-and-beverage/carotenoids-market-fod025c.html

[42] Hamerski, L., Rezende, M.J.C. and Da Silva, B.V. (2013) Usando as cores da natureza para atender aos desejos do consumidor: Substâncias naturais como corantes na indústria alimentícia. *Revista Virtual de Química*, **5**, 394-420.

[43] Bonadio, M.D.P., Freita, L.A.D. and Mutton, M.J.R. (2018) Carotenoid Production in Sugarcane Juice and Synthetic Media Supplemented with Nutrients by *Rhodotorula rubra* L02. *Brazilian Journal of Microbiology*, **49**, 872-878. https://doi.org/10.1016/j.bjm.2018.02.010

[44] Rês, M.V., Francheschi, E., Borges, G.R., Dariva, C., De Castilhos Corazza, F., Oliveira, J.V. and Corazza, M.L. (2007) Influência da temperatura na solubilidade de *β*-Caroteno em solventes orgânicos à pressão ambiente. *Food Science and Technology*, **27**, 737-743. https://doi.org/10.1590/S0101-20612007000400011

[45] Kopec, R.E., Cooperstone, J.L., Cichon, M.J. and Schwartz, S.J. (2012) Analysis Methods of Carotenoids. In: Xu, Z.M. and Luke, R., Eds., *Howard Analysis of Antioxidant-Rich Phytochemicals*, Wiley-Blackwell, Hoboken, 105-149. https://doi.org/10.1002/9781118229378.ch4

[46] Sy, C., Dangles, O., Borel, P. and Caris-Veyrat, C. (2015) Stability of Bacterial Carotenoids in the Presence of Iron in a Model of the Gastric Compartment—Comparison with Dietary Reference Carotenoids. *Archives of Biochemistry and Biophysics*, **572**, 89-100. https://doi.org/10.1016/j.abb.2014.12.030

[47] Krinsky, N.I. (1994) The Biological Properties of Carotenoids. *Pure and Applied Chemistry*, **66**, 1003-1010. https://doi.org/10.1351/pac199466051003

[48] Ahmad, W.A., Ahmad, W.Y.W., Zakaria, Z.A. and Yusof, N.Z. (2012) Application of Bacterial Pigments as Colorant. In: Ahmad, W.A., Ahmad, W.Y.W., Zakaria, Z.A. and Yusof, N.Z., Eds., *Application of Bacterial Pigments as Colorant*, Springer, Berlin, 57-74. https://doi.org/10.1007/978-3-642-24520-6_4

[49] Ceravolo, I.P., Zani, C.L., Figueiredo, F.J., Kohlhoff, M., Santana, A.E. and Krettli, A.U. (2018) Aspidosperma Pyrifolium, a Medicinal Plant from the Brazilian Caatinga, Displays a High Antiplasmodial Activity and Low Cytotoxicity. *Malaria Journal*, **17**, Article No. 436. https://doi.org/10.1186/s12936-018-2568-y

[50] Santos, M.O., Almeida, B.V., Ribeiro, D.A., Macêdo, D.G., Macedo, M.J., Macedo, J.G., Sousa, F.F.D., Oliveira, L.G.D., Saraiva, M.E. and Araujo, T. (2017) The Conservation of Native Priority Medicinal Plants in a Caatinga Area in Ceará, Northeastern Brazil. *Anais da Academia Brasileira de Ciências*, **89**, 2675-2685. https://doi.org/10.1590/0001-3765201720160633

[51] Santos, M.O., Ribeiro, D.A., Macêdo, D.G., Macedo, M.J., Macedo, J.G., Lacerda, M.N.S., Macedo, M.S., Souza, M. and Maria, A. (2018) Medicinal Plants: Versatility and Concordance of Use in the Caatinga Area, Northeastern Brazil. *Anais da Academia Brasileira de Ciências*, **90**, 2767-2779. https://doi.org/10.1590/0001-3765201820170594

[52] Do Nascimento Magalhães, K., Guarniz, W.A.S., Sá, K.M., Freire, A.B., Monteiro, M.P., Nojosa, R.T., Bieski, I.G.C., Custódio, J.B., Balogun, S.O. and Bandeira, M.A.M. (2019) Medicinal Plants of the Caatinga, Northeastern Brazil: Ethnopharmacopeia (1980-1990) of the Late Professor Francisco José de Abreu Matos. *Journal of Ethnopharmacology*, **237**, 314-353. https://doi.org/10.1016/j.jep.2019.03.032

[53] David, J.P., Meira, M., David, J.M., Brandão, H.N., Branco, A., De Fátima Agra, M., Barbosa, M.R.V., De Queiroz, L.P. and Giulietti, A.M. (2007) Radical Scavenging, Antioxidant and Cytotoxic Activity of Brazilian *Caatinga* Plants. *Fitoterapia*, **78**, 215-218. https://doi.org/10.1016/j.fitote.2006.11.015

[54] Martin, V.J., Pitera, D.J., Withers, S.T., Newman, J.D. and Keasling, J.D. (2003) Engineering a Mevalonate Pathway in *Escherichia coli* for Production of Terpenoids. *Nature Biotechnology*, **21**, 796-802. https://doi.org/10.1038/nbt833

[55] Rodrigues, J.P., Prova, S.S., Moraes, L.A.B. and Ifa, D.R. (2018) Characterization and Mapping of Secondary Metabolites of *Streptomyces* sp. from Caatinga by Desorption Electrospray Ionization Mass Spectrometry (DESI-MS). *Analytical and Bioanalytical Chemistry*, **410**, 7135-7144. https://doi.org/10.1007/s00216-018-1315-0

[56] Tian, B. and Hua, Y. (2010) Carotenoid Biosynthesis in Extremophilic Deinococcus-Thermus Bacteria. *Trends in Microbiology*, **18**, 512-520. https://doi.org/10.1016/j.tim.2010.07.007

[57] Duarte, R.T., Nóbrega, F., Nakayama, C.R. and Pellizari, V.H. (2012) Brazilian Research on Extremophiles in the Context of astrobiology. *International Journal of astrobiology*, **11**, 325-333. https://doi.org/10.1017/S1473550412000249

[58] Silva, V., Martins, C.M. and Silveira, S.C. (2015) Atividade celulolítica de actinobactérias de região semiárida do Ceará. *Enciclopédia Biosfera*, **11**, 2026-2036. https://doi.org/10.18677/Enciclopedia_Biosfera_2015_016

[59] Da Silva, I.L., Coel, L.C.B.B. and Da Silva, L.A.D.O. (2015) Biotechnological Potential of the Brazilian Caatinga Biome. *Advances in Research*, **5**, 1-17.

[60] Amsaveni, R., Sureshkumar, M., Vivekanandhan, G., Bhuvaneshwari, V., Kalaiselvi, M., Padmalochana, K. and Preethikaharshini, J. (2015) Screening and Isolation of Pigment Producing Actinomycetes from Soil Samples. *International Journal of Biosciences*, **2**, 24-28.

[61] Kampe, B., Rösch, P. and Popp, J. (2015) Characterization of Carotenoids in Soil Bacteria and investigation of Their Photodegradation by UVA Radiation via Resonance Raman Spectroscopy. *Analyst*, **140**, 4584-4593. https://doi.org/10.1039/C5AN00438A

[62] Kavamura, V.N., Taketani, R.G., Lançoni, M.D., andreote, F.D., Mendes, R. and De Melo, I.S. (2013) Water Regime Influences Bulk Soil and Rhizosphere of *Cereus jamacaru* Bacterial Communities in the Brazilian Caatinga Biome. *PLoS ONE*, **8**, e73606.

[63] Da Silva Andrade, R.F., Lima, R.A., Ribeaux, D.R., Waleska, H., Araújo, C., Franco, L.O., Pessoa-Júnior, A. and Campos-Takaki, G.M. (2016) Production of *β*-Carotene by a Newly Isolated *Rhodotorula glutinis* UCP1555 Strain and Cytotoxic Effect Evaluation. *Journal of Chemistry*, **10**, 212-220. https://doi.org/10.17265/1934-7375/2016.05.003

[64] Freitas, J.V., Lopes, N.P. and Gaspar, L.R. (2015) Photostability Evaluation of Five UV-Filters, Trans-Resveratrol and Beta-Carotene in Sunscreens. *European Journal of Pharmaceutical Sciences*, **78**, 79-89. https://doi.org/10.1016/j.ejps.2015.07.004

[65] Terao, J., Minami, Y. and Bando, N. (2010) Singlet Molecular Oxygen-Quenching Activity of Carotenoids: Relevance to Protection of the Skin from Photoaging. *Journal of Clinical Biochemistry and Nutrition*, **48**, 57-62. https://doi.org/10.3164/jcbn.11-008FR

[66] Tosato, M.G., Orallo, D.E., Fangio, M.F., Diz, V., Dicelio, L.E. and Churio, M.S. (2016) Nanomaterials and Natural Products for UV-Photoprotection. In: Grumezescu, A.M., Ed., *Surface Chemistry of Nanobiomaterials*, Elsevier, Amsterdam, 359-392. https://doi.org/10.1016/B978-0-323-42861-3.00012-1

[67] Darvin, M., Patzelt, A., Gehse, S., Schanzer, S., Benderoth, C., Sterry, W. and Lademann, J. (2008) Cutaneous Concentration of Lycopene Correlates Significantly with the Roughness of the Skin. *European Journal of Pharmaceutics and Biopharmaceutics*, **69**, 943-947. https://doi.org/10.1016/j.ejpb.2008.01.034

[68] Silva, V., Martins, C.M. and Silveira, S.C. (2015) Atividade celulolítica de actinobactérias de região semiárida do Ceará. *Enciclopédia Biosfera*, **11**, 2026-2036. https://doi.org/10.18677/Enciclopedia_Biosfera_2015_016

[69] Loiola, M.I.B., De Araújo Roque, A. and De Oliveira, A.C.P. (2012) Caatinga: Vegetação do semiárido brasileiro. *Notas Técnicas*, **4**, 14-19.