UNIVERSITI PUTRA MALAYSIA

IDENTIFICATION OF MYCOSPORINELIKE AMINO ACIDS AND 3-DEHYDROQUINATE SYNTHASE GENE EXPRESSION IN UV RADIATION-INDUCED Deinococcus radiodurans R1

ALAA HASSAN IBRAHIM AHMED HUWAIDI

FBSB 2018 18

IDENTIFICATION OF MYCOSPORINELIKE AMINO ACIDS AND 3-DEHYDROQUINATE SYNTHASE GENE EXPRESSION IN UV RADIATION-INDUCED *Deinococcus radiodurans* R1

By

ALAA HASSAN IBRAHIM AHMED HUWAIDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

July 2018

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

IDENTIFICATION OF MYCOSPORINELIKE AMINO ACIDS AND 3-DEHYDROQUINATE SYNTHASE GENE EXPRESSION IN UV RADIATION-INDUCED *Deinococcus radiodurans* R1

By

ALAA HASSAN IBRAHIM AHMED HUWAIDI

July 2018

Chairman : Amir Syahir bin Amir Hamzah, PhD
Faculty : Biotechnology and Biomolecular Sciences

Deinococcus radiodurans R1 is a well-known heterotrofic bacterium with extreme radio-resistant capability. It exhibits radiation survival up to 15,000 Gy while still be able to grow normally at 60 Gy/h. The radiation-tolerant mechanism that involves DNA repair represents 20% of the total resistant mechanism. Meanwhile, the other 80% comes from antioxidants. Since *D. radiodurans* R1 was discovered in 1956, the whole radio-resistant mechanism is not yet fully understood. Mycosporine-like amino acids (MAAs) are a group of 40 or more compounds that have antioxidant, growth stimulation and UV protective properties found in many microorganisms. In *D. radiodurans* R1, 3-dehydroquinate synthase (DHQ) gene annotated in chromosome 1 encodes the precursor for all MAAs. In this study, a significant amount of MAAs was found in *D. radiodurans* R1 after treatment with a different type of UV radiations, namely; UVA (360 nm) 6W and 100 W, and UVC (254 nm) 6W at a period of 12 to 48 hours. The RNA and MAAs were isolated from the UV-treated *D. radiodurans* R1. RT-qPCR experiment of the DHQ gene resulted in a significant increase in the number of expression fold from 4 to 9273 fold. Consequently, specific MAAs were identified using time-of-flight mass spectrometry (TOF-MS). They are mycosporine-taurine, mycosporine-glutamine, mycosporine-glutaminol, mycosporine-glutaminol-glucoside, mycosoprine-glycine, mycosporine-2-glycine, mycosporine-glycine:glutamic acid, shinorine, mycosporine-methylamine:serine, palythine-serine, and palythinol. The results suggested that these compounds play essential roles in *D. radiodurans* R1 radio-tolerance especially Mycosporine-methylamine:serine and palythine-serine for its expression at every UV treatment. This study may well help to understand radiation resistance mechanism further, and it is potential to be utilized as human protective compound against radiation risk.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGENALPASTIAN MIKOSPORIN SEPERTI ASID AMINO DAN GEN 3-DEHIDROQUINAT SINTASE PADA *Deinococcus radiodurans* R1 YANG DIDEDAHKAN KEPADA SINAR RADIASI UV

Oleh

ALAA HASSAN IBRAHIM AHMED HUAIDI

Julai 2018

Pengerusi : Amir Syahir bin Amir Hamzah, PhD
Fakulti : Bioteknologi dan Sains Biomolekul

Deinococcus radiodurans R1 adalah bakteria heterotrophik yang terkenal dengan daya ketahannya yang kuat terhadap sinaran radioaktif. Ia mampu bertahan terhadap radiasi sehingga 15,000 Gy sementara masih mampu tumbuhbiak pada 60 Gy/h. Mekanisme anti-radiasi yang melibatkan pengaktifan gen untuk pembaikan DNA mewakili 20% daripada jumlah keseluruhan mekanisme ketahanan radiasi. Selebihnya, 80% diwakili oleh antioksidan. Asid amino seperti mikosporin (MAAs) adalah sekumpulan daripada 40 atau lebih molekul terkandung di dalam banyak mikroorganisma yang mempunyai sifat antioksidan, rangsangan pertumbuhan dan perlindungan UV. Gen penghasilan MAAs disusun pada kromosom 1 *D. radiodurans* R1 di dalam gen 3-dehidroquinate sintase (DHQ). Di dalam kajian ini, sejumlah MAAs telah dikenalpasti terdapat di dalam *D. radiodurans* R1 selepas didedahkan dengan radiasi UV daripada jenis yang berlainan, iaitu UVA (360 nm) 6W dan 100 W, dan UVC (254 nm) 6W selama 12 ke 48 jam. RNA dan MAAs telah berjaya diasingkan daripada spesimen bakteria. Eksperimen RT-qPCR gen DHQ menghasilkan peningkatan ketara dalam bilangan fold ekspresi dari 4 hingga 9273 fold. Sekumpulan MAAs juga telah dapat dikenalpasti dengan menggunakan time-of-flight mass spectrometry (TOF-MS). Ianya terdiri daripada mikosporin-taurina, mikosporin-glutamina, mikosporin-glutaminol, mikosporin-glutaminol-glukosida, mikosporin-glisina, mikosporin-2-glisina, mikosporin-glisina: asid glutamik, shinorina, mikosporin-metilamin:serina, palitin-serina, dan palitinol. Hasil kajian ini mencadangkan bahawa kesemua MAAs terutamanya mikosporin-metilamin:serina dan palitin-serina memainkan peranan yang penting dalam toleransi radiasi dalam setiap pendedahan UV terhadap *D. radiodurans* R1. Kajian ini mencadangkan bahawa kedua-dua kompaun mikosporin-metilamin:serina dan palitin-serina memainkan peranan penting dalam toleransi sinaran pada *D. radiodurans* R1 kerana terdapat pada setiap dedahan UV. Kajian ini juga membantu untuk memahami dengan lebih lanjut berkenaan mekanisme rintangan

radiasi, dan potensi untuk ia digunakan sebagai kompaun perlindungan manusia terhadap risiko radiasi.

ACKNOWLEDGEMENTS

First and foremost, I must thank my advisor, Dr Amir Syahir bin Amir Hamzah, for his guidance, advices and support over the last three years. As much as his mentorship, I appreciate his unwavering trust, which has inspired my own self-confidence as a scientist.

I wish to gratefully acknowledge my co-supervisor, Dr. Noor Azmi Shaharuddin, for his encouragement throughout these years, and his patience in enduring my questions on gene expression experiments. It had made the work more enjoyable and facilitated me a clearer picture in the field of molecular biology.

I would like to take this opportunity to thank the committees in Kyushu Institute of Technology Japan and Associate Professor Dr Shinya IKENO for his support and give me the opportunity to do all my master experiments in his lab.

I thank my co-supervisor, Dr Mahmoud Magdy Abdallah Awad, Senior Lecturer at Genetics Dept., Faculty of Agriculture, Ain Shams University, Egypt. For his guide in qPCR experiments.

Last but not least, I would like to express my deepest gratitude to my wonderful friends, my parent and siblings. Their love and support over the years have made this possible. Graduate school is like running a marathon. The road has been tough at times, but the amazing people who I have encountered over the years have made it worthwhile.

I certify that a Thesis Examination Committee has met on 12 July 2018 to conduct the final examination of Alaa Hassan Ibrahim Ahmed Huwaidi on his thesis entitled "Identification of Mycosporinelike Amino Acids and 3- Dehydroquinate Synthase Gene Expression in UV Radiation-Induced *Deinococcus radiodurans* R1" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Mohd Termizi bin Yusof, PhD
Senior Lecturer
Faculty of Biotechnology and Biomolecular Sciences
Universiti Putra Malaysia
(Chairman)

Syahida binti Ahmad, PhD
Senior Lecturer
Faculty of Biotechnology and Biomolecular Sciences
Universiti Putra Malaysia
(Internal Examiner)

Roohaida binti Othman, PhD
Associate Professor
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 31 October 2018

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Amir Syahir bin Amir Hamzah, PhD
Senior Lecturer
Faculty of Biotechnology and Biomolecular Sciences
Universiti Putra Malaysia
(Chairman)

Noor Azmi Shaharuddin, PhD
Associate Professor
Faculty of Biotechnology and Biomolecular Sciences
Universiti Putra Malaysia
(Member)

Mahmoud Magdy Abdallah Awad, PhD
Senior Lecturer
Department of Genetics, Faculty of Agriculture
Ain Shams University, Egypt
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature:  Date: 28/11/2018

Name and Matric No: Alaa Hassan Ibrahim Ahmed Huwaidi, GS45005

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: _____
Name of Chairman of Supervisory Committee: Dr. Amir Syahir bin Amir Hamzah

Signature: _____
Name of Member of Supervisory Committee: Associate Professor Dr. Noor Azmi Shaharuddin

Signature: _____
Name of Member of Supervisory Committee: Dr. Mahmoud Magdy Abdallah Awad

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

RT-qPCR	Real-Time Quantification Polymerase Chain Reaction
PCR	Polymerase Chain Reaction
cDNA	Complementary DNA
TOF-MS	Time of Flight Mass Spectrometry
MAAs	Mycosporine-Like Amino Acids
ROS	Reactive oxygen species
CPD	Cyclobutane Pyrimidine Dimers
^{o}C	Degree Celsius
UV-A	Ultraviolet A
UV-B	Ultraviolet B
UV-C	Ultraviolet C
PDR	Post-desiccation recovery
DHQ	3-dehydroquinate synthase
M-tau	Mycosporine-taurine
M-Gln	Mycosporine-glutamine
M-Gln(OH)	Mycosporine-glutaminol
MGG	Mycosporine-Glutaminol-Glucoside
M-Gly	Mycosporine-glycine
M-2-G	Mycosporine-2-glycine
M-Gly:Glu	Mycosporine-Glycine:Glutamic Acid
SH	Shinorine
MMS	Mycosporine-methylamine:serine
PS	Palythine-serine
M+H	M+1 Hydrogen
M+K	M+39 Potassium
M+Na	M+23 Sodium

CHAPTER 1

INTRODUCTION

Deinococcus radiodurans R1 is a well-known extreme radio-resistant and non-pathogenic gram-positive bacterium with a heterotrophic lifestyle (Makarova et al., 2001). It exhibits radiation survival trait of 15,000 Gy (1Gy=100 Rad). Besides, it can grow contiguously at 60 Gy/h (Makarova et al., 2001; Wan et al., 2013). For comparison, 2 to 5 Gy may kill a human, while *E. coli* can survive up to 200 to 800 Gy (Blasius et al., 2008; Battista, 1997; Piechura et al., 2015). Information on the mechanism of radiation resistance of the *D. radiodurans* R1 is limited since its discovery in 1956 (Wan et al., 2013). The whole genome sequencing of *D. radiodurans* R1 has been performed by White et al. (1999) reporting that the genome comprises two chromosomes (2,648,638 and 412,348 bp); a mega-plasmid (177,466 bp) and a small plasmid (45,704 bp) resulting in the overall genome size of 3.2 Mbp. It is known that only 20% of the DNA impairment of *D. radiodurans* R1 directly happens through radiation wave while the other 80% indirectly occurs from the action of reactive oxygen species (ROS) (Ghosal et al., 2005).

D. radiodurans R1 radiation resistance mechanism is classified into three portions; cellular cleansing, which is when oxidized nucleotide is disintegrated by hydrolases while other harmful constituents are transferred away from the cells; antioxidant defense by the ROS scavenging system that comprises superoxide dismutase (SOD), catalase, carotenoids, manganese ($Mn2^{+}$) and vitamins A, E.; and lastly DNA reparation through nucleotide excision repaired and stretched synthesis reliant strand annealing with energetic homologous rearrangement (Daly, 2004; Luan et al., 2014).

Oxidative stress is experienced through ROS that could be produced metabolically or when exposed to a physical and chemical substance such as desiccation, ionizing radiation, UV radiation, mitomycin C (MMC) and hydrogen peroxide (Slade and Radman, 2011). ROS destroys lipids, proteins, carbohydrates as well as nucleic acids and induces fatal double-stranded DNA breakdowns (DSBs) in the genome of bacteria, which can upset the entire cellular macromolecules (Daly, 2009). D. radiodurans R1 exhibits significant resistance for the entire ROS-generating agents unequalled among the entire acknowledged species (Slade and Radman, 2011).

D. radiodurans R1 can breakdown its genome to many fragments (as many as 2,000 DSBs per multi-genomic cell) without producing substantial protein destruction (Daly et al., 2007). The toughness of the bacterium is based on the robust oxidative stress resistance mechanisms that shield the proteins form destruction resulted from oxidation (Daly et al., 2007) and DNA reparation that effectively completes the exact DNA fragments reassembly (Slade et al., 2009; Zahradka et al., 2006). The antioxidation protection of DNA repair and other proteins enables them to retain their catalytic activity and to provide a swift response under the conditions of oxidative stress.

Conventionally, DNA is considered the target of initial radiation. The current study in D. radiodurans R1 revealed that the bacterium is vulnerable to radiation induce DSBs like other species (Gérard et al., 2001), while its proteome is better shielded against ROS-induced oxidative destruction compared to other radiation sensitive species (Daly et al., 2007). These discoveries advocate that it is the protein destruction level that persists in radiation and not the destruction of DNA (Daly et al., 2007; Daly et al., 2010).

Mycosporine-like amino acids (MAAs) are an assemblage of 40 or higher number of colourless molecules that can dissolve in water and can take up UV-A and UV-B radiation and diffuse the energy into a moderate. MAAs have been reported in the microbial world, for example, in heterotrophic bacteria, cyanobacteria, macro, micro-algae, phytoplankton and protozoan (Sinha et al., 2007). The MAAs display a high variety of molecular arrangement, with molecular weight ranging from 188 to 1050 Daltons. The employment of extensive diversity of organisms comprising eukaryotic and prokaryotes micro-organisms which reside in the terrestrial, marine and aquatic habitat of MAAs have been done (Wada et al., 2015).

The characteristics advocate that MAAs are steady and essential molecules permitting the organisms to survive in UV radiation. Therefore, MAAs is believed to be significantly essential at an early stage in life on the globe, which functions as a principal sunscreen in reducing the impact of short wavelength light. MAAs are the ring systems of cyclohexenone or cyclohexenimine chromophore with a glycine subunit on the third position of the carbon atom and sulphate ester or glycosidic linkage (Sinha and Häder, 2008; Sinha et al., 2007). It has antioxidant properties, growth stimulation activity in human and UV protection role (Misonou et al., 2003; Oyamada et al., 2008).

In cyanobacteria and other organisms, the origin molecule of all MAAs 3-dehydroquinate is produced by 3-dehydroquinate synthase (DHQ) (Gabani and Singh, 2013; Wada et al., 2015). D. radiodurans R1 has the DHQ synthase gene annotated in chromosome 1 GenBank accession numbers: DR_0777 (DHQ) (White et al., 1999). Nevertheless, the association of MAAs production concerning the radiation-tolerance in D. radiodurans R1 is yet to be revealed.

1.1 Problem Statement

Since *D. radiodurans* R1 was discovered in 1956, the whole radio-resistant mechanism is not yet fully understood. About 80% of the repairing mechanism is believed to come from antioxidants such as carotenoids, $Mn2^{+}$ and vitamins A, E. Until now, there is no record of measuring DHQ gene, that produces MAAs in *D. radiodurans* R1.

1.2 Hypothesis

MAAs are predicted to have functions in *D. radiodurans* R1 in radiation tolerance. Thus during the UV-radiation induced stress, particular MAAs are expected to be synthesized.

1.3 Objectives

In response to the radiation treatment, the objectives of this study are:

1. To identify the types of MAAs in *D. radiodurans* R1 expressed under UV-radiation (different wavelengths) induced stress.
2. To measure DHQ gene expression in *D. radiodurans* R1 under UV-radiation induction.

REFERENCES

Ahmed, H., Padey, A., & Pathak, J. (2017). Comparative In silico Analysis of Different Dehydroquinate Synthase Proteins in the *Cyanobacterium cyanothece Sp.* PCC 7424. *J Bioinform, Genomics, Proteomics 2*(2), 1018.

Attri, P., & Choi, E. H. (2013). Influence of reactive oxygen species on the enzyme stability and activity in the presence of ionic liquids. *PloS One*, 8(9), e75096.

Al-Naggar, R. A., Al-Naggar, T. H., & Bobryshev, Y. V. (2011). Perceptions and opinions towards skin cancer prevention in Malaysia: a qualitative approach. *Asian Pac J Cancer Prev*, *12*(4), 995–999.

Balskus, E. P., & Walsh, C. T. (2010). The genetic and molecular basis for sunscreen biosynthesis in cyanobacteria. *Science*, *329*(5999), 1653–1656.

Banaszak, A. T., & Trench, R. K. (1995). Effects of ultraviolet (UV) radiation on marine microalgal-invertebrate symbioses. II. The synthesis of mycosporine-like amino acids in responce to exposure to UV in *Anthopleura elegantissma* and *Cassiopeia xamachan*a. *Journal of Exprimental Marine Biology and Ecology*, *194*(2), 233–250.

Banaszak, A., LaJeunesse, T. C., & Trench, R. K. (2000). The synthesis of mycosporine-like amino acids (MAAS) by cultured, symbiotic dinoflagellates. *Journal of Experimental Marine Biology and Ecology*, *249*(2), 219–233.

Battista, J. R. (1997). Against All Odds:The Survival Strategies of *Deinococcus radiodurans*. *Annual Review of Microbiology*, *51*(1), 203–224.

Battista, J. R., Earl, A. M., & Park, M. J. (1999). Why is *Deinococcus radiodurans* so resistant to ionizing radiation?. *Trends in microbiology, 7*(9), 362–365.

Battista, J. R., Park, M. J., & McLemore. (2001). Inactivation of two homologues of proteins presumed to be involved in the desiccation tolerance of plants sensitizes *Deinococcus radiodurans* R1 to desiccation. *Cryobiology*, *43*(2), 133–139.

Bemis, J. E., & Bourne, D. J. (1996). Ultraviolet Absorbinf Pigments from the Marine Sponge Dysidea herbacea Isolation and Structure of a New Mycosporine.pdf. *Comparative Biochemistry and Physiology*, *115*(3), 281–286.

Bentley, R., & Haslam, E. (1990). The shikimate pathway- a metabolic tree with many branche. *Critical reviews in biochemistry and molecular biology*, 25(5), 307–384.

Bernillon, J., Bouillant, M. L., Pittet, J. L., Favre-Bonvin, J., & Arpin, N. (1984). Mycosporine glutamine and related mycosporines in the fungus Pyronema omphalodes. *Phytochemistry*, *23*(5), 1083–1087.

Bernillon, J., Parussini, E., Letoublon, R., Favre-Bonvin, J., & Arpin, N. (1990). Flavin-mediated photolysis of mycosporines. *Phytochemistry*, *29*(1), 81–84.

Bhatia, S., Sharma, K., Sharma, A., Garg, A., Kumar, S., & Purohit, A. (2011). Mycosporine and mycosporine-like amino acids: A paramount tool against ultra violet irradiation. *Pharmacognosy Reviews*, *5*(10), 138.

Blasius, M., Hübscher, U., & Sommer, S. (2008). *Deinococcus radiodurans* : What Belongs to the Survival Kit? *Critical Reviews in Biochemistry and Molecular Biology*, *43*(3), 221–238.

Braune, W., & Dohler, G. (1996). N-15-uptake, influenced by UV-B radiation, and pattern of amino-acid pools during akinete germination in Anabaena variabilis (Cyanobacteria). *Journal of Basic Microbiology*, *36*(4), 219–227.

Browne, N., Donovan, F., Murray, P., & Saha, S. K. (2014). Cyanobacteria as bio-factories for production of UV-screening compounds. *OA Biotechnology*, (1), 1–7.

Buscot, F., & Bernillon, J. (1991). Mycosporins and related compounds in field and cultured mycelial structures of Morchella esculenta. *Mycological Research*, *95*(6), 752–754.

Cabiscol, E., Tamarit, J., & Ros, J. (2000). Oxidative stress in bacteria and protein damage by reactive oxygen species. *International Microbiology*, *3*(1), 3–8.

Campbell, S. A., Richards, T. A., Mui, E. J., Samuel, B. U., Coggins, J. R., McLeod, R., & Roberts, C. W. (2004). A complete shikimate pathway in Toxoplasma gondii: An ancient eukaryotic innovation. *International Journal for Parasitology*, *34*(1), 5–13.

Carefoot, T. H., Harris, M., Tayler, B. E., Donovan, D., & Karentz, D. (1998). Mycosporine-like amino acids: possible UV protection in eggs of the seahare Aplysia dactylomela. *Mar. Biol.*, *130*(3), 389–396.

Carignan, M. O., Cardozo, K. H. M., Oliveira-Silva, D., Colepicolo, P., & Carreto, J. I. (2009). Palythine-threonine, a major novel mycosporine-like amino acid (MAA) isolated from the hermatypic coral Pocillopora capitata. *Journal of Photochemistry and Photobiology B: Biology*, *94*(3), 191–200.

Carreto, J. I., & Carignan, M. O. (2011). Mycosporine-like amino acids: Relevant secondary metabolites. chemical and ecological aspects. *Marine Drugs*, *9*(3), 387–446.

Casati, P., & Walbot, V. (2003). Gene Expression Profiling in Response to Ultraviolet Radiation in Maize Genotypes with Varying. *Society*, *132*(8), 1739–1754.

Chang, X., Yang, L., Zhao, Q., Fu, W., Chen, H., Qiu,Shu, W. (2010). Involvement of recF in 254 nm ultraviolet radiation resistance in *Deinococcus radiodurans* and *Escherichia coli*. *Current Microbiology*, *61*(5), 458–464.

Cheewinthamrongrod, V., Kageyama, H., Palaga, T., Takabe, T., & Waditee-Sirisattha, R. (2016). DNA damage protecting and free radical scavenging properties of mycosporine-2-glycine from the Dead Sea cyanobacterium in A375 human melanoma cell lines. *Journal of Photochemistry and Photobiology B: Biology*, *164*, 289–295.

Chioccara, F., Misuraca, G., Novellino, E., & Prota, G. (1979). Occurrence of two new mycosporine-like aminoacids, mytilins A and B in the edible mussel, mytilus galloprovincialis. *Tetrahedron Letters*, *20*(34), 3181–3182.

Chrapusta, E., Kaminski, A., Duchnik, K., Bober, B., Adamski, M., & Bialczyk, J. (2017). Mycosporine-Like Amino Acids: Potential health and beauty ingredients. *Marine Drugs*, *15*(10), 1–29.

Cox, M. M., & Battista, J. R. (2005). *Deinococcus radiodurans*-the consummate survivor. *Nature Reviews Microbiology*, *3*(11), 882.

Cubillos, V. M., Burritt, D. J., Lamare, M. D., & Peake, B. M. (2015). The relationship between UV-irradiance, photoprotective compounds and DNA damage in two intertidal invertebrates with contrasting mobility characteristics. *Journal of Photochemistry and Photobiology B: Biology*, *149*, 280–288.

Cuypers, A., Plusquin, M., Remans, T., Jozefczak, M., Keunen, E., Gielen, H., Smeets, K. (2010). Cadmium stress: An oxidative challenge. *BioMetals*, *23*(5), 927–940.

Carroll, A. K., & Shick, J. M. (1996). Dietary accumulation of UV-absorbing mycosporine-like amino acids (MAAs) by the green sea urchin (Strongylocentrotus droebachiensis). *Marine Biology, 124*(4), 561–569.

Conde, F. R., Churio, M. S., & Previtali, C. M. (2004). The deactivation pathways of the excited-states of the mycosporine-like amino acids shinorine and porphyra-334 in aqueous solution. *Photochemical & Photobiological Sciences, 3*(10), 960–967.

D'Agostino, P. M., Javalkote, V. S., Mazmouz, R., Pickford, R., Puranik, P. R., & Neilan, B. A. (2016). Comparative profiling and discovery of novel glycosylated mycosporine-like amino acids in two strains of the cyanobacterium Scytonema cf. crispum. *Applied and Environmental Microbiology*, *82*(19), 5951–5959.

Dainton, F. S. (1948). On the Existence of Free Atoms and Radicals in Water and Aqueous Solutions Subjected to Ionizing Radiation. *The Journal of Physical and Colloid Chemistry*, *52*(3), 490–517.

Daly, M. J., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Zhai, M., Venkateswaran, A.,& Wackett, L. P. (2004). Accumulation of Mn (II) in *Deinococcus radiodurans* facilitates gamma-radiation resistance. Science, 306(5698), 1025–1028.

Daly, M. J. (2006). Modulating Radiation Resistance: Insights Based on Defenses Against Reactive Oxygen Species in the Radioresistant Bacterium *Deinococcus radiodurans*. *Clinics in Laboratory Medicine*, *26*(2), 491–504.

Daly, M. J. (2009). A new perspective on radiation resistance based on *Deinococcus radiodurans*. *Nature Reviews. Microbiology*, *7*(3), 237–245.

Daly, M. J., Gaidamakova, E. K., Matrosova, V. Y., Kiang, J. G., Fukumoto, R., Lee, D. Y., Levine, R. L. (2010). Small-molecule antioxidant proteome-shields in *Deinococcus radiodurans*. *PLoS ONE*. 5(9), e12570.

Daly, M. J., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Zhai, M., Leapman, R. D., Fredrickson, J. K. (2007). Protein oxidation implicated as the primary determinant of bacterial radioresistance. *PLoS Biology 5*(4), e92.

Daly, M. J., & Minton, K. W. (1996). An alternative pathway of recombination of chromosomal fragments precedes recA-dependent recombination in the radioresistant bacterium *Deinococcus radiodurans*. *Journal of Bacteriology*, *178*(15), 4461–4471.

Daly, M. J., & Minton, K. W. (1997). Recombination between a resident plasmid and the chromosome following irradiation of the radioresistant bacterium *Deinococcus radiodurans*. *Gene*, *187*(2), 225–229.

Daniel, S., Cornelia, S., & Fred, Z. (2004). UV-A sunscreen from red algae for protection against premature skin aging. *Cosmet and Toiletries Manufact Worldwid*, 129, 139–143.

De Groot, A., Chapon, V., Servant, P., Christen, R., Fischer-Le Saux, M., Sommer, S., & Heulin, T. (2005). *Deinococcus deserti* sp. nov., a gamma-radiation-tolerant bacterium isolated from the Sahara Desert. *International Journal of Systematic and Evolutionary Microbiology*, *55*(6), 2441–2446.

De La Coba, F., Aguilera, J., Figueroa, F. L., De Gálvez, M. V., & Herrera, E. (2009). Antioxidant activity of mycosporine-like amino acids isolated from three red macroalgae and one marine lichen. *Journal of Applied Phycology*, *21*(2), 161–169.

Devasagayam, T. P. A., Tilak, J., Boloor, K. K., Sane, K. S., Ghaskadbi, S. S., & Lele, R. D. (2004). Free radicals and antioxidants in human health: current status and future prospects. *J Assoc Physicians India*, *52*(10), 794–804.

Ding, L., Hofius, D., Hajirezaei, M. R., Fernie, A. R., Börnke, F., & Sonnewald, U. (2007). Functional analysis of the essential bifunctional tobacco enzyme 3-dehydroquinate dehydratase/shikimate dehydrogenase in transgenic tobacco plants. *Journal of Experimental Botany*, *58*(8), 2053–2067.

Dionisio-Sese, M. L. (2010). Aquatic microalgae as potential sources of UV-screening compounds. *Philippine Journal of Science*, *139*, 5–16.

Dittami, S. M., Gravot, A., Renault, D., Goulitquer, S., Eggert, A., Bouchereau, A., … Tonon, T. (2011). Integrative analysis of metabolite and transcript abundance during the short-term response to saline and oxidative stress in the brown alga Ectocarpus siliculosus. *Plant, Cell and Environment*, *34*(4), 629–642.

Döhler, G. (1997). Effect of UVB Radiation on Utilization of Inorganic Nitrogen by Antarctic Microalgae. *Photochemistry and Photobiology*, *66*: 831–836.

Döhler, G., & Buchmann, T. (1995). Effects of UV-A and UV-B Irradiance on Pigments and 15N-Ammonium Assimilation of the Haptophycean Pavlova. *Journal of Plant Physiology*, *146*(1–2), 29–34.

Duan, Y., Yao, X., Zhu, J., Li, Y., Zhang, J., Zhou, X., Li, X. (2017). Effects of yak‐activated protein on hematopoiesis and related cytokines in radiation‐induced injury in mice. *Experimental and Therapeutic Medicine*, 5297–5304.

Dunlap, W. C., & Shick, J. M. (1998). Ultraviolet Radiation-Absorbing Mycosporine-Like Amino Acids in Coral Reef Organisms: a Biochemical and Environmental Perspective. *Journal of Phycology*, *34*(3), 418–430.

Dunlap, W. C., & Yamamoto, Y. (1995). Small-molecule antioxidants in marine organisms: Antioxidant activity of mycosporine-glycine. *Comparative Biochemistry and Physiology - Part B: Biochemistry and*, *112*(1), 105–114.

Earl, A. M., Rankin, S. K., Kim, K., Oleana, N., Battista, J. R., & Lamendola, O. N. (2002). Genetic Evidence that the uvsE Gene Product of *Deinococcus radiodurans* R1 is a UV Damage Endonuclease Genetic Evidence that the uvsE Gene Product of *Deinococcus radiodurans* R1 Is a UV Damage Endonuclease, *184*(4), 1003–1009.

Favre-Bonvin, J., Bernillon, J., Salin, N., & Arpin, N. (1987). Biosynthesis of mycosporines: Mycosporine glutaminol in Trichothecium roseum. *Phytochemistry*, *26*(9), 2509–2514.

Feng, Y. N., Zhang, Z. C., Feng, J. L., & Qiu, B. S. (2012). Effects of UV-B radiation and periodic desiccation on the morphogenesis of the edible terrestrial cyanobacterium nostoc flagelliforme. *Applied and Environmental Microbiology*, *78*(19), 7075–7081.

Ferrier-Pagès, C., Richard, C., Forcioli, D., Allemand, D., Pichon, M., & Shick, J. M. (2007). Effects of temperature and UV radiation increases on the photosynthetic efficiency in four scleractinian coral species. *The Biological Bulletin, 213*(1), 76–87.

Fournier, M., Aubert, C., Dermoun, Z., Durand, M. C., Moinier, D., & Dolla, A. (2006). Response of the anaerobe Desulfovibrio vulgaris Hildenborough to oxidative conditions: Proteome and transcript analysis. *Biochimie*, *88*(1), 85–94.

Gabani, P., & Singh, O. V. (2013). Radiation-resistant extremophiles and their potential in biotechnology and therapeutics. *Applied Microbiology and Biotechnology*, *97*(3), 993–1004.

Ganapathy, K., Chidambaram, K., Janarthanan, R., & Ramasamy, R. (2017). Effect of UV-B radiation on growth, photosynthetic activity and metabolic activities of Chlorella vulgaris. *Journal of Microbiology and Biotechnology*, 6 (2017), 53–60.

Gao, Q., & Garcia-Pichel, F. (2011). Microbial ultraviolet sunscreens. *Nature Reviews Microbiology*, *9*(11), 791–802.

Gérard, E., Jolivet, E., Prieur, D., & Forterre, P. (2001). DNA protection mechanisms are not involved in the radioresistance of the hyperthermophilic archaea Pyrococcus abyssi and P. furiosus. *Molecular Genetics and Genomics*, *266*(1), 72–78.

Ghosal, D., Omelchenko, M. V., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Venkateswaran, A., … Daly, M. J. (2005). How radiation kills cells: Survival of *Deinococcus radiodurans* and Shewanella oneidensis under oxidative stress. *FEMS Microbiology Reviews*, *29*(2), 361–375.

Gorbushina, A. (2003). Microcolonial fungi: survival potential of terrestrial vegetative structures. *Astrobiology*, *3*(3), 543–54.

Gourley, D. G., Shrive, A. K., Polikarpov, I., Krell, T., Coggins, J. R., Hawkins, A. R., Sawyer, L. (1999). The two types of 3-dehydroquinase have distinct structures but catalyze the same overall reaction. *Nature Structural Biology*, *6*(6), 521–525.

Gutman, P. D., Yao, H., & Minton, K. W. (1991). Partial complementation of the UV sensitivity of *Deinococcus radiodurans* excision repair mutants by the cloned denV gene of bacteriophage T4. *Mutation Research-DNA Repair*, *254*(3), 207–215.

Herrmann, K. M. (1995). The Shikimate Pathway as an Entry to Aromatic Secondary Metabolism. *Plant Physiology*, *107*(1), 7–12.

Houston, M. (2005). Nutraceuticals, Vitamins, Antioxidants, and Minerals in the Prevention and Treatment of Hypertension. *Progress in Cardiovascular Diseases*, *47*(6), 396–449.

Hoyer, K., Karsten, U., Sawall, T., & Wiencke, C. (2001). Photoprotective substances in Antarctic macroalgae and their variation with respect to depth distribution, different tissues and developmental stages. *Marine Ecology Progress Series*, *211*, 117–129.

Hudson, C. L., & Ferrier, M. D. (2008). Assessing ultraviolet radiation-induced DNA damage and repair in field-collected Aiptasia pallida using the comet assay. *Proceedings of the 11th International Coral Reef Symposium*, (5), 7–11.

Imlay, J. A. (2003). Pathways of Oxidative Damage. *Annual Review of Microbiology*, *57*(1), 395–418.

Ilyas, M. (2007). Climate augmentation of erythemal UV-B radiation dose damage in the tropics and global change. *Current Science*, 1604–1608.

Jain, S., Prajapat, G., Abrar, M., Ledwani, L., Singh, A., & Agrawal, A. (2017). Cyanobacteria as efficient producers of mycosporine-like amino acids. *Journal of Basic Microbiology*, *57*(9), 715–727.

Jin, H. L., Sung, Y. K., In, S. K., & Park, J. W. (2007). Regulation of ionizing radiation-induced apoptosis by mitochondrial NADP+-dependent isocitrate dehydrogenase. *Journal of Biological Chemistry*, *282*(18), 13385–13394.

Jurkiewicz, B. A., Tner, R. B. U. E., & Buettner, R. (1994). Ultraviolet light-induced free radical formation in skin: an electron paramagnetic resonance study. *Photochemistry and Photobiology*, *59*(I), 1–4.

Karentz, D., McEuen, F. S., Land, M. C., & Dunlap, W. C. (1991). Survey of mycosporine-like amino acid compounds in Antarctic marine organisms: potential protection from ultraviolet exposure. *Marine Biology*, *108*(1), 157–166.

Katoch, M., Mazmouz, R., Chau, R., Pearson, L. A., Pickford, R., & Neilan, B. A. (2016). Heterologous production of cyanobacterial mycosporine-like amino acids mycosporine-ornithine and mycosporine-lysine in *E. coli*. *Applied and environmental microbiology*, AEM–01632.

Kedar, L., Kashman, Y., & Oren, A. (2002). Mycosporine-2-glycine is the major mycosporine-like amino acid in a unicellular cyanobacterium (Euhalothece sp.) isolated from a gypsum crust in a hypersaline saltern pond. *FEMS Microbiology Letters*, *208*(2), 233–237.

Kogej, T., Gostinčar, C., Volkmann, M., Gorbushina, A. A., & Gunde-Cimerman, N. (2006). Mycosporines in extremophilic fungi - Novel complementary osmolytes? *Environmental Chemistry*, *3*(2), 105–110.

Korbee, N., Mata, M. T., & Figueroa, F. L. (2010). Photoprotection mechanisms against ultraviolet radiation in Heterocapsa sp. (Dinophyceae) are influenced by nitrogen availability: Mycosporine-like amino acids vs. xanthophyll cycle. *Limnology and Oceanography*, *55*(2), 899–908.

Kräbs, G., Bischof, K., Hanelt, D., Karsten, U., & Wiencke, C. (2002). Wavelength-dependent induction of UV-absorbing mycosporine-like amino acids in the red alga Chondrus crispus under natural solar radiation. *Journal of Experimental Marine Biology and Ecology*, *268*(1), 69–82.

Ujaoney, A. K., Padwal, M. K., & Basu, B. (2017). Proteome dynamics during post-desiccation recovery reveal convergence of desiccation and gamma radiation stress response pathways in *Deinococcus radiodurans*. *Biochimica et Biophysica Acta (BBA)-Proteins and Proteomics, 1865*(9), 1215–1226.

Lange, C. C., Wackett, L. P., Minton, K. W., & Daly, M. J. (1998). Engineering a recombinant *Deinococcus radiodurans* for organopollutant degradation in radioactive mixed waste environments. *Nature Biotechnology*, *16*(10), 929–933.

Lavy, A., Neeman, Y., & Fuhrman, B. (2005). The antioxidative effect of the bacteria *Dienococcus radiophilus* against LDL lipid peroxidation. *European Journal of Nutrition*, *44*(5), 281–284.

Lesser, M. P., Farrell, J. H., & Walker, C. W. (2001). Oxidative stress, DNA damage and p53 expression in the larvae of atlantic cod (Gadus morhua) exposed to ultraviolet (290-400 nm) radiation. *The Journal of Experimental Biology*, *204*(1), 157–64.

Liu, Y., Zhou, J., Omelchenko, M. V, Beliaev, A. S., Venkateswaran, A., Stair, J., … Daly, M. J. (2003). Transcriptome dynamics of *Deinococcus radiodurans* recovering from ionizing radiation. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(15), 4191–4196.

Livak, K. J., & Schmittgen, T. D. (2001). Analysis of relative gene expression data using real-time quantitative PCR and the 2-ΔΔCT method. *Methods*, *25*(4), 402–408.

Lown, J. W., Sim, S. K., & Chen, H. H. (1978). Hydroxyl radical production by free and DNA-bound aminoquinone antibiotics and its role in DNA degradation. Electron spin resonance detection of hydroxyl radicals by spin trapping. *Canadian Journal of Biochemistry*, *56*(11), 1042–1047.

Li, X., & Lu, A. L. (2001). Molecular cloning and functional analysis of the MutY homolog of *Deinococcus radiodurans*. *Journal of bacteriology*, 183(21), 6151–6158.

Luan, H., Meng, N., Fu, J., Chen, X., Xu, X., Feng, Q., ... & Roberts, A. A. (2014). Genome-wide transcriptome and antioxidant analyses on gamma-irradiated phases of *deinococcus radiodurans* R1. *PloS one*, 9(1), e85649.

Makarova, K. S., Aravind, L., Wolf, Y. I., Tatusov, R. L., Minton, K. W., Koonin Eugene V., A., & Daly, M. J. (2001). Genome of the Extremely Radiation-Resistant Bacterium. *Microbiology and Molecular Biology Reviews*, *65*(1), 44–79.

McClintock, J. B., & Karentz, D. (1997). Mycosporine-like amino acids in 38 species of subtidal marine organisms from McMurdo Sound, Antarctica. *Antarctic Science*, *9*(4), 392–398.

Mckenzie, R. L., Mckenzie, R., Connor, B., & Bodeker, G. (1999). Increased Summertime UV Radiation in New Zealand in Response to Ozone Loss Increased Summertime UV Radiation in New Zealand in Response to Ozone Loss, *285*(9), 1709–1712.

Melin, a. M., Peuchant, E., Perromat, a., & Clerc, M. (1998). Sensitivity to oxidative damage of two Deinococcus radiodurans strains. *Journal of Applied Microbiology*, *84*(4), 531–537.

Michalek-Wagner, K. (2001). Seasonal and sex-specific variations in levels of photo-protecting mycosporine-like amino acids (MAAs) in soft corals. *Marine Biology*, *139*, 651–660.

Michalek-Wagner, K., & Willis, B. L. (2001). Impacts of bleaching on the soft coral Lobophytum compactum. II. Biochemical changes in adults and their eggs. *Coral Reefs*, *19*(3), 240–246.

Minton, K. (1994). DNA repair in the extremely radioresistant bacterium *Deinococcus radiodurans*. *Molecular Microbiology*, *13*(1), 9–15.

Misonou, T., Saitoh, J., Oshiba, S., Tokitomo, Y., Maegawa, M., Inoue, Y., Sakurai, T. (2003). UV-Absorbing Substance in the Red Alga Porphyra yezoensis (Bangiales, Rhodophyta) Block Thymine Photodimer Production. *Marine Biotechnology*, *5*(2), 194–200.

Moe, E., Leiros, I., Smalås, A. O., & McSweeney, S. (2006). The crystal structure of mismatch-specific uracil-DNA glycosylase (MUG) from *Deinococcus radiodurans* reveals a novel catalytic residue and broad substrate specificity. *Journal of Biological Chemistry*, *281*(1), 569–577.

Moliné, M., Arbeloa, E. M., Flores, M. R., Libkind, D., Farías, M. E., Bertolotti, S. G., van Broock, M. R. (2011). UVB Photoprotective Role of Mycosporines in Yeast: Photostability and Antioxidant Activity of Mycosporine-Glutaminol-Glucoside. *Radiation Research*, *175*(1), 44–50.

Montero, O., & Lubián, L. M. (2003). Mycosporine-like amino acid (MAAs) production by Heterocapasa sp. (Dinophyceae) in indoor cultures. *Biomolecular Engineering*, *20*(4–6), 183–189.

Muszynski, F. Z., Bruckner, A., Armstrong, R. A., Morell, J. M., & Corredor, J. E. (1998). Within-colony variations of UV absorption in a reef building coral. *Bulletin of Marine Science*, *63*(3), 589–594.

Negron, L., Patchett, M. L., & Parker, E. J. (2011). Expression, Purification, and Characterisation of Dehydroquinate Synthase from Pyrococcus furiosus. *Enzyme Research*, *2011*, 134893.

Hoong Ng, K. (2003). Non-Ionizing Radiations - Sources, Biological Effects, Emissions and Exposures. *Proceedings of the International Conference on Non-Ionizing Radiation at UNITEN*, (10), 1–16.

Niki, E. (1990). Free radical initiators as source of water-or lipid-soluble peroxyl radicals. In Methods in enzymology, *Academic Press* (Vol. 186, pp. 100–108).

Nimse, S. B., & Pal, D. (2015). Free radicals, natural antioxidants, and their reaction mechanisms. *RSC Advances*, *5*(35), 27986–28006.

Ognjanović, B. I., Marković, S. D., Pavlović, S. Z., Zikić, R. V, Stajn, a S., & Saicić, Z. S. (2008). Effect of chronic cadmium exposure on antioxidant defense system in some tissues of rats: protective effect of selenium. *Physiological Research / Academia Scientiarum Bohemoslovaca*, *57*(3), 403–411.

Olsson-Francis, K., Watson, J. S., & Cockell, C. S. (2013). Cyanobacteria isolated from the high-intertidal zone: A model for studying the physiological prerequisites for survival in low Earth orbit. *International Journal of Astrobiology*, *12*(4), 292–303.

Oren, A., & Gunde-Cimerman, N. (2007). Mycosporines and mycosporine-like amino acids: UV protectants or multipurpose secondary metabolites? *FEMS Microbiology Letters*, *269*(1), 1–10.

Oyamada, C., Kaneniwa, M., Ebitani, K., Murata, M., & Ishihara, K. (2008). Mycosporine-like amino acids extracted from scallop (Patinopecten yessoensis) ovaries: UV protection and growth stimulation activities on human cells. *Marine Biotechnology*, *10*(2), 141–150.

Pallela, R., Na-Young, Y., & Kim, S. K. (2010). Anti-photoaging and photoprotective compounds derived from marine organisms. *Marine Drugs*, *8*(4), 1189–1202.

Paredes-Molina, F. J., Cubillos, V. M., Montory, J. A., & Andrade-Villagrán, P. A. (2016). Are embryonic developing modes determinant in the acquisition and levels of photoprotective compounds in slipper limpets of the Crepipatella genus? *Journal of Photochemistry and Photobiology B: Biology*, *162*(July), 511–518.

Park, H. L., Lee, S. W., Jung, K. H., Hahn, T. R., & Cho, M. H. (2013). Transcriptomic analysis of UV-treated rice leaves reveals UV-induced phytoalexin biosynthetic pathways and their regulatory networks in rice. *Phytochemistry*, *96*, 57–71.

Petit, C., & Sancar, A. (1998). Nucleotide excision repair: From *E. coli* to man. *Biochimie*, *81*, 15–25.

Piechura, J. R., Tseng, T. L., Hsu, H. F., Byrne, R. T., Windgassen, T. A., Chitteni-Pattu, S., … Cox, M. M. (2015). Biochemical characterization of RecA variants that contribute to extreme resistance to ionizing radiation. *DNA Repair*, *26*, 30–43.

Portwich, A., & Garcia-Pichel, F. (1999). Ultraviolet and osmotic stresses induce and regulate the synthesis of mycosporines in the cyanobacterium Chlorogloeopsis PCC 6912. *Archives of Microbiology*, *172*(4), 187–192.

Portwich, A., & Garcia-Pichel, F. (2003). Biosynthetic pathway of mycosporines (mycosporine-like amino acids) in the cyanobacterium Chlorogloeopsis sp. strain PCC 6912. *Phycologia*, *42*(4), 384–392.

Potts, M. (1994). Desiccation tolerance of prokaryotes. *Microbiological Reviews*, *58*(4), 755–805.

Roberts, F., Roberts, C. W., Johnson, J. J., Kyle, D. E., Krell, T., Coggins, J. R., & Chakrabarti, D. (1998). Evidence for the shikimate pathway in apicomplexan parasites. *Nature*, *393*(6687), 801.

Rainey, F. A., Ray, K., Ferreira, M., Gatz, B. Z., Nobre, M. F., Bagaley, D., Da Costa, M. S. (2005). Extensive diversity of ionizing-radiation-resistant bacteria recovered from Sonoran Desert soil and description of nine new species of the genus *Deinococcus* obtained from a single soil sample. *Applied and Environmental Microbiology*, *71*(9), 5225–5235.

Rajpurohit, Y. S., & Misra, H. S. (2013). DR1769, a protein with N-terminal beta propeller repeats and a low-complexity hydrophilic tail, plays a role in desiccation tolerance of *Deinococcus radiodurans*. *Journal of Bacteriology*, *195*(17), 3888–3896.

Rastogi, R. P., Kumari, S., Richa, Han, T., & Sinha, R. P. (2012). Molecular characterization of hot spring cyanobacteria and evaluation of their photoprotective compounds. *Canadian Journal of Microbiology*, *58*(6), 719–727.

Rastogi, R. P., Madamwar, D., & Incharoensakdi, A. (2015). Sun-screening bioactive compounds mycosporine-like amino acids in naturally occurring cyanobacterial biofilms: Role in photoprotection. *Journal of Applied Microbiology*, *119*(3), 753–762.

Rastogi, R. P., Richa, Sinha, R. P., Singh, S. P., & Häder, D.-P. (2010). Photoprotective compounds from marine organisms. *Journal of Industrial Microbiology & Biotechnology*, *37*(6), 537–558.

Rastogi, R. P., Sonani, R. R., & Madamwar, D. (2017). UV Photoprotectants From Algae—Synthesis and Bio-Functionalities. *Algal Green Chemistry*, (pp. 17–38).

Richa, & Sinha, R. P. (2014). Biochemical characterization of sunscreening mycosporine-like amino acids from two Nostoc species inhabiting diverse habitats. *Protoplasma*, *252*(1), 199–208.

Richa, Sinha R.P., Häder DP. (2016) Effects of Global Change, Including UV and UV Screening Compounds. In The Physiology of Microalgae. Developments in Applied Phycology, vol 6. *Springer, Cham* (pp. 373–409)

Rosic, N. N. (2012). Phylogenetic analysis of genes involved in mycosporine-like amino acid biosynthesis in symbiotic dinoflagellates. *Applied Microbiology and Biotechnology*, *94*(1), 29–37.

Roullier, C., Chollet-Krugler, M., Pferschy-Wenzig, E. M., Maillard, A., Rechberger, G. N., Legouin-Gargadennec, B., Boustie, J. (2011). Characterization and identification of mycosporines-like compounds in cyanolichens. Isolation of mycosporine hydroxyglutamicol from Nephroma laevigatum Ach. *Phytochemistry*, *72*(11–12), 1348–1357.

Schomburg D., Schomburg I and Chang A. (2010) 3-Dehydroquinate synthase. Isomerases, Ligases. Springer Handbook of Enzymes, vol S7. Springer, Berlin.

Sandigursky, M., Sandigursky, S., Sonati, P., Daly, M. J., & Franklin, W. A. (2004). Multiple uracil-DNA glycosylase activities in *Deinococcus radiodurans*. *DNA Repair*, *3*(2), 163–169.

Scandalios, J. G. (2005). Oxidative stress: Molecular perception and transduction of signals triggering antioxidant gene defenses. *Brazilian Journal of Medical and Biological Research*, *38*(7), 995–1014.

Seed, T. M., Inal, C. E., & Singh, V. K. (2014). Radioprotection of hematopoietic progenitors by low dose amifostine prophylaxis. *International Journal of Radiation Biology*, *90*(7), 594–604.

Shahidi, F. & Zhong, Y. (2010). Novel antioxidants in food quality preservation and health promotion. *European Journal of Lipid Science and Technology*, *112*(9), 930–940.

Sheridan, A. M., Fitzpatrick, S., Wang, C., Wheeler, D. C., & Lieberthal, W. (1996). Lipid peroxidation contributes to hydrogen peroxide induced cytotoxicity in renal epithelial cells. *Kidney International*, *49*(1), 88–93.

Shick, J.M., Lesser, M.P., Stochaj, W. R. (1991). Ultraviolet radiation and photooxidative stress in zooxanthellate Anthozoa: the sea anemone Phyllodiscis semoni and the octocoral Clavularia sp. *Symbiosis*. 10, 145–173

Shick, J., Lesser, M., Dunlap, W., & Stochaj, W. (1995). Depth-dependent responses to solar ultraviolet radiation and oxidative stress in the zooxanthellate coral Acropora microphthalma. *Marine Biology*, *122*(1), 41–51.

Shick, J. M. (2004). The continuity and intensity of ultraviolet irradiation affect the kinetics of biosynthesis, accumulation, and conversion of mycosporine-like amino acids (MAAs) in the coral Stylophora pistillata. *Limnology and Oceanography*, *49*(2), 442–458.

Shick, J. M., Dunlap, W. C., Pearse, J. S., & Pearse, V. B. (2002a). Mycosporine-like amino acid content in four species of sea anemones in the genus Anthopleura reflects phylogenetic but not environmental or symbiotic relationships. *Biological Bulletin*, *203*(3), 315–330.

Shick, J. M., & Dunlap, W. C. (2002b). Mycosporine-Like Amino Acids and Related Gadusols: Biosynthesis, Accumulation, and UV-Protective Functions in Aquatic Organisms. *Annual Review of Physiology*, *64*(1), 223–262.

Shick, J. M., Romaine-Lioud, S., Romaine-Lioud, S., Ferrier-Pagès, C., & Gattuso, J.-P. (1999). Ultraviolet-B radiation stimulates shikimate pathway-dependent accumulation of mycosporine-like amino acids in the coral Stylophora pistillata despite decreases in its population of symbiotic dinoflagellates. *Limnology and Oceanography*, *44*(7), 1667–1682.

Shukla, M., Chaturvedi, R., Tamhane, D., Vyas, P., Archana, G., Apte, S., Desai, A. (2007). Multiple-stress tolerance of ionizing radiation-resistant bacterial isolates obtained from various habitats: Correlation between stresses. *Current Microbiology*, *54*(2), 142–148.

Shukla, V., Kumari, R., Patel, D. K., & Upreti, D. K. (2016). Characterization of the diversity of mycosporine-like amino acids in lichens from high altitude region of Himalaya. *Amino Acids*, *48*(1), 129–136.

Siddique, Y. H., Ara, G., & Afzal, M. (2012). Estimation of lipid peroxidation induced by hydrogen peroxide in cultured human lymphocytes. *Dose-Response*, *10*(1), 1–10.

Singh, S. P., Kumari, S., Rastogi, R. P., Singh, K. L., & Sinha, R. P. (2008a). Mycosporine-like amino acids (MAAs): Chemical structure, biosynthesis and significance as UV-absorbing/screening compounds. *Indian Journal of Experimental Biology*, *46*(1), 7–17.

Singh, S. P., Klisch, M., Sinha, R. P., & Häder, D. P. (2008b). Effects of abiotic stressors on synthesis of the mycosporine-like amino acid shinorine in the cyanobacterium anabaena variabilis PCC 7937. *Photochemistry and Photobiology*, *84*(6), 1500–1505.

Singh, S. P., Klisch, M., Häder, D. P., & Sinha, R. P. (2008c). Role of various growth media on shinorine (mycosporine-like amino acid) concentration and photosynthetic yield in Anabaena variabilis PCC 7937. *World Journal of Microbiology and Biotechnology*, *24*(12), 3111–3115.

Singh, S. P., Sinha, R. P., Klisch, M., & Häder, D. P. (2008d). Mycosporine-like amino acids (MAAs) profile of a rice-field cyanobacterium Anabaena doliolum as influenced by PAR and UVR. *Planta*, *229*(1), 225–233.

Singh, S. P., Klisch, M., Sinha, R. P., & Häder, D. P. (2010). Genome mining of mycosporine-like amino acid (MAA) synthesizing and non-synthesizing cyanobacteria: A bioinformatics study. *Genomics*, *95*(2), 120–128.

Sinha, R. P. (2015). Stability, Antioxidative and Pharmaceutical Potentials of Porphyra-334 Isolated From a Hot-Spring Cyanobacterium Nostoc sp. Strain HKAR-2. *Human Journals Research Article April Ijppr.Human*, *3*(31), 94–111.

Sinha, R. P., & Häder, D. P. (2008). UV-protectants in cyanobacteria. *Plant Science*, *174*(3), 278–289.

Sinha, R. P., Klisch, M., Gröniger, A., & Häder, D. P. (1998). Ultraviolet-absorbing/screening substances in cyanobacteria, phytoplankton and macroalgae. *Journal of Photochemistry and Photobiology B: Biology*, *47*(2–3), 83–94.

Sinha, R. P., Klisch, M., & Häder, D. P. (1999). Induction of a mycosporine-like amino acid (MAA) in the rice-field cyanobacterium Anabaena sp. by UV irradiation. *Journal of Photochemistry and Photobiology B: Biology*, *52*(1–3), 59–64.

Sinha, R. P., Klisch, M., Walter Helbling, E., & Häder, D. P. (2001). Induction of mycosporine-like amino acids (MAAs) in cyanobacteria by solar ultraviolet-B radiation. *Journal of Photochemistry and Photobiology B: Biology*, *60*(2–3), 129–135.

Sinha, R. P., Singh, S. P., & Häder, D. P. (2007). Database on mycosporines and mycosporine-like amino acids (MAAs) in fungi, cyanobacteria, macroalgae, phytoplankton and animals. *Journal of Photochemistry and Photobiology B: Biology*, *89*(1), 29–35.

Slade, D., Lindner, A. B., Paul, G., & Radman, M. (2009). Recombination and Replication in DNA Repair of Heavily Irradiated *Deinococcus radiodurans*. *Cell*, *136*(6), 1044–1055.

Slade, D., & Radman, M. (2011). Oxidative Stress Resistance in *Deinococcus radiodurans*. *Microbiology and Molecular Biology Reviews* (Vol. 75).

Sommaruga, R., & Garcia-Pichel, F. (1999). UV-absorbing mycosporine-like compounds planktonic and benthic organisms from a high-mountain lake. *Archive Fur Hydrobiologie.*, (February), 255–269.

Sommaruga, R., Libkind, D., van Broock, M., & Whitehead, K. (2004). Mycosporine-glutaminol-glucoside, a UV-absorbing compound of two Rhodotorula yeast species. *Yeast*, *21*(13), 1077–1081.

Starcevic, A., Dunlap, W. C., Cullum, J., Malcolm Shick, J., Hranueli, D., & Long, P. F. (2010). Gene expression in the scleractinian Acropora microphthalma exposed to high solar irradiance reveals elements of photoprotection and coral bleaching. *PLoS ONE*, *5*(11).

Stochaj, W. R., Dunlap, W. C., & Shick, J. M. (1994). Two new UV-absorbing mycosporine-like amino acids from the sea anemone Anthopleura elegantissima and the effects of zooxanthellae and spectral irradiance on chemical composition and content. *Marine Biology*, *118*(1), 149–156.

Suh, S. S., Hwang, J., Park, M., Seo, H. H., Kim, H. S., Lee, J. H., Lee, T. K. (2014). Anti-inflammation activities of mycosporine-like amino acids (MAAs) in response to UV radiation suggest potential anti-skin aging activity. *Marine Drugs*, *12*(10).

Sukhi, S. S., Shashidhar, R., Kumar, S. A., & Bandekar, J. R. (2009). Radiation resistance of *Deinococcus radiodurans* R1 with respect to growth phase. *FEMS microbiology letters, 297*(1), 49-53.

Tan, K. C., Lim, H. S., & Mat Jafri, M. Z. (2016). Study on solar ultraviolet erythemal dose distribution over Peninsular Malaysia using Ozone Monitoring Instrument. *The Egyptian Journal of Remote Sensing and Space Science*, *21*(1), 105–110.

Tanaka, M., Earl, A. M., Howell, H. A., Park, M. J., Eisen, J. A., Peterson, S. N., & Battista, J. R. (2004). Analysis of *Deinococcus radiodurans* transcriptional response to ionizing radiation and desiccation reveals novel proteins that contribute to extreme radioresistance. *Genetics*, *168*(1), 21–33.

Tanaka, M., Narumi, I., Funayama, T., Kikuchi, M., Watanabe, H., Matsunaga, T., … Yamamoto, K. (2005). Characterization of Pathways Dependent on the uvsE, uvrA1, or uvrA2 Gene Product for UV Resistance in *Deinococcus radiodurans*. *Society*, *187*(11), 3693–3697.

Tavernier, S. (2010). Experimental techniques in nuclear and particle physics.*Springer-Verlag Berlin Heidelberg* 2010. 23–53

Teai, T., Drollet, J. H., Bianchini, J.-P., Cambon, A., & Martin, P. M. V. (1998). Occurrence of ultraviolet radiation-absorbing mycosporine-like amino acids in coral mucus and whole corals of French Polynesia. *Marine and Freshwater Research*, *49*(2), 127.

Teai, T., Drollet, J. H., Bianchini, J. P., Cambon, A., & Martin, P. M. V. (1997a). Widespread occurrence of mycosporine-like amino acid compounds in scleractinians from French Polynesia. *Coral Reefs*, *16*(3), 169–176.

Teai, T. T., Raharivelomanana, P., Bianchini, J. P., Faure, R., Martin, P. M. V, & Cambon, A. (1997b). Structure De Deux Nouvelles Iminomycosporines Isolees De Pocillopora Eydouxi. *Tetrahedron Letters*, *38*(33), 5799–5800.

Tirkey, J., & Adhikary, S. P. (2005). Cyanobacteria in biological soil crusts of India. *Current Science*, *89*(3), 515–521.

Ujaoney, A. K., Potnis, A. A., Kane, P., Mukhopadhyaya, R., & Apte, S. K. (2010). Radiation desiccation response motif-like sequences are involved in transcriptional activation of the deinococcal ssb gene by ionizing radiation but not by desiccation. *Journal of Bacteriology*, *192*(21), 5637–5644.

United Nations. Scientific Committee on the Effects of Atomic Radiation. (2000). Sources and effects of ionizing radiation: sources (Vol. 1) pp 2-13. *United Nations Publications*.

Vafa, O., Wade, M., Kern, S., Beeche, M., Pandita, T. K., Hampton, G. M., & Wahl, G. M. (2002). c-Myc can induce DNA damage, increase reactive oxygen species, and mitigate p53 function: A mechanism for oncogene-induced genetic instability. *Molecular Cell*, *9*(5), 1031–1044.

Villa, J. K., Amador, P., Janovsky, J., Bhuyan, A., Saldanha, R., Lamkin, T. J., & Contreras, L. M. (2017). A genome-wide search for ionizing-radiationresponsive elements in *Deinococcus radiodurans* reveals a regulatory role for the DNA gyrase subunit A gene's 5' untranslated region in the radiation and desiccation response. *Applied and Environmental Microbiology*, *83*(12), 1–19.

Volkmann, M., & Gorbushina, A. A. (2006). A broadly applicable method for extraction and characterization of mycosporines and mycosporine-like amino acids of terrestrial, marine and freshwater origin. *FEMS Microbiology Letters*, *255*(2), 286–295.

Volkmann, M., Whitehead, K., Rütters, H., Rullkötter, J., & Gorbushina, A. A. (2003). Mycosporine-glutamicol-glucoside: a natural UV-absorbing secondary metabolite of rock-inhabiting microcolonial fungi. *Rapid Communications in Mass Spectrometry*, *20*(16), 2520.

Volodymyr, I. L. (2011). Adaptive response to oxidative stress: Bacteria, fungi, plants and animals. *Comparative Biochemistry and Physiology. Toxicology & Pharmacology : CBP*, *153*(2), 175–190.

Wada, N., Sakamoto, T., & Matsugo, S. (2015). Mycosporine-Like Amino Acids and Their Derivatives as Natural Antioxidants. *Antioxidants*, *4*(3), 603–646.

Waditee-Sirisattha, R., Kageyama, H., Fukaya, M., Rai, V., & Takabe, T. (2015). Nitrate and amino acid availability affects glycine betaine and mycosporine-2-glycine in response to changes of salinity in a halotolerant cyanobacterium Aphanothece halophytica. *FEMS Microbiology Letters*, *362*(23), 1–6.

Waditee-Sirisattha, R., Kageyama, H., Sopun, W., Tanaka, Y., & Takabe, T. (2014). Identification and upregulation of biosynthetic genes required for accumulation of mycosporine-2-glycine under salt stress conditions in the halotolerant cyanobacterium Aphanothece halophytica. *Applied and Environmental Microbiology*, *80*(5).

Wan, P. (2013). Mechanisms of Radiation Resistance in *Deinococcus radiodurans* R1 Revealed by the Reconstruction of Gene Regulatory Network Using Bayesian Network Approach. *Journal of Proteomics & Bioinformatics*, *1*(S6), 6–10.

Wang, P., & Schellhorn, H. E. (1995). Induction of resistance to hydrogen peroxide and radiation in *Deinococcus radiodurans*. *Canadian Journal of Microbiology*, *41*(2), 170–6.

Watkinson, J. I., Sioson, A. A., Vasquez-robinet, C., Shukla, M., Kumar, D., Ellis, M., … Grene, R. (2003). Photosynthetic Acclimation Is Reflected in Specific Patterns of Gene Expression in Drought-Stressed Loblolly Pine 1 [w]. *Society*, *133*(12), 1702–1716.

Werth, V. P., & Zhang, W. (1999). Wavelength-specific synergy between ultraviolet radiation and interleukin-1α in the regulation of matrix-related genes: Mechanistic role for tumor necrosis factor-α. *Journal of Investigative Dermatology*, *113*(2), 196–201.

White, O., Eisen, J. A., Heidelberg, J. F., Hickey, E. K., Peterson, J. D., Dodson, R. J., Fraser, C. M. (1999). Genome sequence of the radioresistant bacterium *Deinococcus radiodurans* R1. *Science (New York, N.Y.)*, *286*(5444), 1571–7.

Wright, D. J., Smith, S. C., Joardar, V., Scherer, S., Jervis, J., Warren, A., … Potts, M. (2005). UV irradiation and desiccation modulate the three-dimensional extracellular matrix of Nostoc commune (Cyanobacteria). *Journal of Biological Chemistry*, *280*(48), 40271–40281.

Xiong, F., Kopecky, J., & Nedbal, L. (1999). The occurrence of UV-B absorbing mycosporine-like amino acids in freshwater and terrestrial microalgae (Chlorophyta). *Aquatic Botany*, *63*(1), 37–49.

Yakovleva, I., Bhagooli, R., Takemura, A., & Hidaka, M. (2004). Differential susceptibility to oxidative stress of two scleractinian corals: Antioxidant functioning of mycosporine-glycine. *Comparative Biochemistry and Physiology - B Biochemistry and Molecular Biology*, *139*(4), 721–730.

Yakovleva, I., & Hidaka, M. (2004). Diel fluctuations of mycosporine-like amino acids in shallow-water scleractinian corals. *Marine Biology*, *145*(5), 863–873.

Yang, P., Chen, Z., Shan, Z., Ding, X., Liu, L., & Guo, J. (2014). Effects of FMN riboswitch on antioxidant activity in *Deinococcus radiodurans* under H2O2 stress. *Microbiological Research*, *169*(5–6), 411–416.

Yasui, A., & McCready, S. J. (1998). Alternative repair pathways for UV-induced DNA damage. *BioEssays*, *20*(4), 291–297.

Young, H., & Patterson, V. J. (1982). A uv protective compound from Glomerella cingulata- a mycosporine. *Phytochemistry*, 21(5), 1075–1077.

Young, I. S., & Woodside, J. V. (2001). Antioxidants in health and disease Antioxidants in health and disease. *Journal of Clinical Pathology*, 176–186.

Zahradka, K., Slade, D., Bailone, A., Sommer, S., Averbeck, D., Petranovic, M., … Radman, M. (2006). Reassembly of shattered chromosomes in *Deinococcus radiodurans*. *Nature*, *443*, 569.

Zhang, H.-Y., Li, X., Gao, N., & Chen, L.-L. (2009). Antioxidants used by *Deinococcus radiodurans* and implications for antioxidant drug discovery. *Nature Reviews Microbiology*, *7*(6), 476–476.

Zhang, L., Li, L., & Wu, Q. (2007a). Protective effects of mycosporine-like amino acids of Synechocystis sp. PCC 6803 and their partial characterization. *Journal of Photochemistry and Photobiology B: Biology*, *86*(3), 240–245.

Zhang, L., Yang, Q., Luo, X., Fang, C., Zhang, Q., & Tang, Y. (2007b). Knockout of crtB or crtI gene blocks the carotenoid biosynthetic pathway in *Deinococcus radiodurans* R1 and in X uences its resistance to oxidative DNA-damaging agents due to change of free radicals scavenging ability, *Archives of microbiology*, 188(4), 411–419.

Zhang, M., Bi, L. F., Fang, J. H., Su, X. L., Da, G. L., Kuwamori, T., & Kagamimori, S. (2004). Beneficial effects of taurine on serum lipids in overweight or obese non-diabetic subjects. *Amino Acids*, *26*(3), 267–271.

Zhang, W., Culley, D. E., Hogan, M., Vitiritti, L., & Brockman, F. J. (2006). Oxidative stress and heat-shock responses in Desulfovibrio vulgaris by genome-wide transcriptomic analysis. *Antonie van Leeuwenhoek, International Journal of General and Molecular Microbiology*, *90*(1), 41–55.

Zhang, Z. Z., Li, X. X., Chu, Y. N., Zhang, M. X., Wen, Y. Q., Duan, C. Q., & Pan, Q. H. (2012). Three types of ultraviolet irradiation differentially promote expression of shikimate pathway genes and production of anthocyanins in grape berries. *Plant Physiology and Biochemistry*, *57*, 74–83.