Physiological aspects of the halophilic and halotolerant fungi, and their potential applications

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Abstract

Extremophiles are organisms that can thrive under extreme environmental conditions. There are many types of extremophiles, which require different growth conditions and habitats to grow; among them are the halophilic and the halotolerant microbes. These microbes are reported to grow in habitats of high salinity regions including the sea, sediments, lakes, mines, plant and the soil. They need high carbon source and salt concentration to achieve maximum tolerable condition for their survival. High salinity survival and tolerance of these microbes are mechanized due to their osmotic and ionic stress, which are regulated through their genetic expression of enzymes, proteins, cell wall compositions and transporters. Thus, due to their robustness; the halophiles and halotolerant fungi showed high potential in health care; antimicrobial and anticancer activity, nanoparticle synthesis, enzyme production, genetics, bioremediation and other aspects. The aim of the current study was to explore the halophilic and halotolerant fungi, which are least explored for their habitats, growth requirements, and mechanism for salt resistance and tolerance. This will be followed by their biotechnological applications focusing on the biomedical industry, due to the emergence of the new multi-drug resistant pathogenic microbes.

Keywords: Extremophiles, Fungi, Halophiles, Halotolerant, Physiology
1. Introduction

Extremophilic microbes survive under extreme ecosystems such as hot; cold, salty, sandy, highly acidic and alkaline habitats, due to their physiological and metabolic activities. Because of their robustness, the extremophilic microbes not only have more attention as sources of novel bioactive compounds, but also for understanding the basis of evolution of life (Chung et al., 2019). It is observed that halophilic microorganisms were studied for their stress adaptation mechanisms and biotechnological applications (Chamekh et al., 2019). Halophilic fungi had been previously isolated from different habitats including terrestrial; aquatic, decaying matter and dried foods (González-Abadelo et al., 2019; Tafer et al., 2019; Pérez-Llano et al., 2020). High salt tolerating groups are more diverse and all types of microorganisms such as bacteria; algae, fungi and protozoa have been studied from different environmental and geographical samples (Chamekh et al., 2019). Halophilic bacteria are the most dominantly studied halophiles, compared to the halophilic fungi. The literatures and available reports showed that halophilic fungi have greater potential in terms of exploration of novel species with new bioactivities. Thus, the objective of the current study was to exploit the halophilic and halotolerant fungi; with a special focus on their physiological and biotechnological applications.

2. Habitats

A previous study of Ali et al., (2019) revealed that salt concentration makes categorization of the halophiles as slight halophiles (2-5 %), moderate halophiles (5-20 %) and extreme halophiles (20-30 %). Fungal diversity is very important, and the physiological behavior as well as metabolic secretions varies according to the geographical locations. The solar salterns; dead sea, arid desert, sebkha, soil, terrestrial habitats mud had been explored for their biodiversity studies (Moubasher et al., 2018; Chamekh et al., 2019). The biodiversity studies explored Aspergillus sp. strain A4, Chaetomium sp. strain H1, Penicillium vinaceum, Gymnoascus halophilus, Wallemia sp. and Ustilago cynodontis fungi from the great Sebkha of Oran, Algeria (Chamekh et al., 2019). Recently, Aspergillus glaucus is known to be ‘China Changchun halophilic Aspergillus (CCHA)’, which was isolated from the surface of plants growing near a salt mine in Jilin, China (Qiu et al., 2020). Fungi isolated from Miani-Hor Mangrove Forest Soil from Pakistan were recorded to be Aspergillus chevalieri; Pleosporaceae spp., Alternaria tenuissima and A. alternata (Khan et al., 2020). G. halophilus and Wallemia spp. were isolated from the Lake soil located in Algeria (Chamekh et al., 2019). A previous study conducted by González-Martínez et al., (2017) reported that sediment samples are sources of the halophilic fungi. Scopulariopsis spp.; Aspergillus spp., Peniophora spp. and Cladosporium spp. have been isolated from the Gulf sediment located in North America (González-Martínez et al., 2017). Similarly, Corral et al., (2018) highlighted that P. rubens and A. protuberus were isolated from Bonna sediment located in New England. Since the halophiles are known for their salt tolerance; exploration of salt mine and saltern has resulted in the discovery of diversified species including; A. salisburgensis isolated from a salt mine (Tafer et al., 2019), Wallemia ichthyophaga and Paramerita triangularis from solar saltern (Primožič et al., 2019) and Yarrowia lipolytica recovered from solar saltern saline (Alamillo et al., 2017). Other habitats include plants such as A. glaucus isolated from leave surface (Qiu et al., 2020) and A. montevidensis ZYD4 from Medicago sativa L. Plant (Liu et al., 2017a). Sugarcane bagasse is also recorded to be the habitat for halotolerant fungi such as A. sydowii (González-Abadelo et al., 2019). Results presented in Table. (1) demonstrate habitats of the halophilic and the halotolerant fungi, where it can be noticed that Aspergillus spp. are more dominant and located at every regional habitat.
Table 1: Different habitats of the halophilic fungi around the world (2017-2021)

| Halophilic\Halotolerant fungi | Habitat | Country        | Reference                        |
|-------------------------------|---------|----------------|----------------------------------|
| *A. chevalieri*, *Pleosporaceae* spp., *Alternaria tenuissima*, *A. alternata* | Miani-Hor Mangrove Forest Soil | Pakistan | (Khan et al., 2020) |
| *Gymnoascus halophilus*, *Wallemia* sp. | Great Sebkha (Lake) Soil | Algeria | (Chamekh et al., 2019) |
| *A. glaucus* | Plant surface | China | (Qiu et al., 2020) |
| *A. destruens* | Canvass of an oil painting | Slovenia | (González-Abradelo et al., 2019) |
| *Wallemia chthyophaga* *Paranerita triangularis* | Solar saltern | Slovenia | (Primožič et al., 2019) |
| *A. sydowii* | Sugarcane Bagasse | Slovenia | (González-Abradelo et al., 2019) |
| *Scopulariopsis* sp.: *Aspergillus* sp.: *Peniophora* sp. and *Cladosporium* sp. | Gulf Sediments | North America | (González-Martínez et al., 2017) |
| *Magnuscella marinae* | Sponge sample | Europe | (Anteneh et al., 2019) |
| *A. loretoensis* | marine sediment of Loreto Bay | California | (González-Martínez et al., 2019) |
| *A. atacamensis*, *A. salisburgensis* | Old wooden staircase in a salt mine | Austria | (Martinelli et al., 2017) |
| *A. loretoensis* | Marine sediment of Loreto Bay | México | (González-Martínez et al., 2019) |
| *A. salisburgensis*, *A. sclerotialis* | Salt Mines | Austria | (Tafer et al., 2019) |
3. Isolation and nutritional requirements of the halophilic fungi

Isolation of the halophilic fungi from the microbial communities of high salt contents is challenging, and mainly depends on the enrichment followed by cultivation using different nutritional parameters (Anteneh et al., 2019). Diversities among the halophilic or the halotolerant fungi depend on their habitats and physiological requirements. Ruginescu et al., (2020) reported that the mechanisms used by these types of microorganisms to handle the osmotic pressure exerted with the high salt concentration of the surrounding medium are extremely diverse. Ability of the halophilic microorganisms to adapt to wide range of environments is attributed to the physicochemical conditions including overall salinity; temperature and nutritional status, which is reflected in their heterogeneity within the different communities (Menasria et al., 2019). Many salt habitats have been described as suitable for the survival of halophiles such as; the lakes and rivers, salterns, soils, salted foods, leaves of some plants and wall paintings (Ruginescu et al., 2020).

| Halophilic Fungi | Carbon Source | Place of Isolation             | Country     | Ref.                           |
|-----------------|---------------|-------------------------------|-------------|-------------------------------|
| A. montevidensis ZYD4 | Medicago sativa L. plant | China                      | Liu et al., 2017a |
| Yarrowia lipolytica | Solar salter saline | Mexico                     | Alamillo et al., 2017 |
| Penicillium rubens, P. chrysogenum | Goliat oil field | -                           | Corral et al., 2018 |
| P. chrysogenum | Repparfjord coastal | Norway                      | Corral et al., 2018 |
| P. rubens, A. protuberus | Bonna sediment | New England                 | Corral et al., 2018 |
| A. sydowii, Microascus trigonosporus | Sea | Kansas                      | Corral et al., 2018 |

The nutritional and cultivation parameters of the halophilic fungi includes carbon source; pH of medium, temperature and salt concentration. The most commonly used media for isolation of halophilic fungi include potato dextrose agar (Chamekh et al., 2019; Qiu et al., 2020), yeast extract peptone dextrose agar (González-Martínez et al., 2017) and malt extract agar (Pérez-Llano et al., 2020); with the reported incubation period of 7 days (González-Martínez et al., 2019). The media ingredients contain carbon sources with high concentration of sugars, which support the growth of fungi. The study conducted by Anteneh et al., (2019) highlighted that the lower acid pH produced during fermentation helps in bacterial inhibition; sometimes antibiotics may be supplemented in the medium for bacterial inhibition. Table. (2) shows isolation of the different halophilic fungi at different locations; based on their cultivational and nutritional parameters. González-Martínez et al., (2017) found that the majority of halophilic fungi are growing within 7-15 days; with two contradictory reports from the Gulf Sediments, Mexico, reporting the requirement of lower growth period of 48 h for Scopulariopsis sp., Aspergillus sp., Peniophora sp., Cladosporium sp., whereas a longer growth period of 2 months is required for Cladosporium spp.; Aspergillus sp. and
Other study of Anteneh et al., (2019) revealed that Magnuscella marinae which was isolated from marine sponge samples of Australia required two months to be cultivated in different media supplemented with higher salt concentrations. Therefore, the geographical locations have different cultivation and nutritional requirements, but hold the main functions for the individual fungal physiology.

Table 2: Isolation of halophilic fungal spp. based on different cultivation and nutritional parameters (2017-2021)

| Halophilic fungi          | Source                     | Cultivation parameters | Nutritional parameters                                                                 | References                           |
|--------------------------|----------------------------|------------------------|----------------------------------------------------------------------------------------|--------------------------------------|
| A sydowii BMH-0004       | Sugarcane bagasse, Mexico | 7 days at 30-37°C      | Malt extract agar (MEA), Czapek yeast extract agar (CYA), Creatine-sucrose agar (CREA) with 5% NaCl | (Pérez-Llano et al., 2020)           |
| Magnus cellaruminae      | Sponge sample, Marine, Australia | 27°C in dark for 2 months | Starch yeast extract peptone agar (SYP), Asparagine peptone agar (APA), Natural seawater agar (SWA), Humic acid vitamin agar (HV), Nutrient agar (NA), Marine agar (MA), Tryptone soya agar (TSA with different concentrations of NaCl (0-30%)) | (Anteneh et al., 2019)               |
| Scopulariopsis sp., Aspergillus sp., Peniophora sp., Cladosporium sp. | Gulf Sediments, Loreto Bay, California, Baja Mexico. | 18-20°C in dark for 48 h | Yeast extract peptone dextrose (YPED) agar with 100% seawater | (González-Martínez et al., 2017)    |
| Aspergillus sp., G. halophilus, Fusarium sp., Chaetomium sp., Microascus manginii, Cladosporium sp. | Soil sample, Great Sebkha of Oran, Northwestern of Algeria | 25°C for 10 days | Potato dextrose agar with NaCl conc. 0- to 20%; with an interval of 2.5% | (Chamekh et al., 2019)              |
| A glaucus ‘CCHA’          | Solar salt field, Northeast China | 6 days at 30°C         | Potato extract + 20 g/l glucose, supplemented with 250 g/l NaCl                         | (Qiu et al., 2020)                  |
| Species                        | Location                        | Temperature | Media Description                                                                                           | References                                                                 |
|-------------------------------|---------------------------------|-------------|------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| *M. marinae*                  | Sponge samples, South Australia | 27°C for 3 weeks | 1, 2, 3, 4, 5, 10, 15, 25, and 30% NaCl + Potato dextrose media                                           | (Anteneh et al., 2019)                                                   |
|                               | marine environments             |             |                                                                                                             |                                                                           |
| *Cladosporium* sp., *Aspergillus* sp., *Talaromyces* sp. | Gulf Sediments, Loreto-bay, Mexico | 2 months, at room temperature (RT) | YEPD agar (yeast extract peptone dextrose agar + ampicillin 50 μg/ml) + 50% natural filtered (0.45 μm) seawater | (González-Martínez et al., 2017)                                        |
|                               |                                 |             |                                                                                                             |                                                                           |
| *A. sydowii, A. destruens*    | Sugarcane bagasse, canvass of an oil painting, Slovenia | 15 days at 28°C | Synthetic saline medium (SM) and MEA agar plates with added NaCl (MEA-SM), benzo-α-pyrene and phenanthrene (1:1) | (González-Abradelo et al., 2019)                                       |
|                               |                                 |             |                                                                                                             |                                                                           |
| *Trimatostroma salinum, Wallemia ichthyophaga, Hortaea werneckii, Phaeotheca triangularis* | Solar salterns, Slovenian | 5-7 days, RT | Malt extract agar + 17% NaCl | (Primožič et al., 2019)                                              |
| *A. protuberus* MUT 3638      | Sub-sea sediments, Barents Sea   | 7 to 14 days, RT | Artificial seawater media \Seawater minimal medium\ Malt extract agar\ Luria bertani + 3, 5, 10, 15, 20 and 25% NaCl | (Corral et al., 2018)                                                   |

4. Salt tolerance mechanisms of the halophilic fungal spp.

Fugal species that tolerate high salinity are known as halo tolerant fungi, which can withstand the high osmotic pressure (water loss from the fungal cells and built up of solutes in the cytosol), and the ionic stress (rise in the level of Na\(^+\)). According to Gunde-Cimerman et al., (2018), fungal adaptation necessitates their ability to tolerate fluctuating salinities and higher salt concentration. The use of compatible solutes is the most representative technique for salt adaptation, as presented in *Hortaea werneckii* and *Wallemia ichthyophaga* by Plemenitas et al., (2014). A previous study conducted by Chung et al., (2019) highlighted those fungi that are grown in saline containing media; accumulate compatible solutes in the cytosol in order to keep the intracellular Na\(^+\) below the toxic levels. *A. sydowii* had been studied extensively due to its osmo protective strategies during the optimal and extreme saline conditions. Modification in the thickness of the cell wall and the lamellar structure; along with decrease in the chitin content and rise in the content of α and β-glucan were observed. Furthermore, a change...
in the hydrophobin gene expression under high salinity was also reported (Pérez-Llano et al., 2020). The proteome of A. sclerotialis showed increased proportion of alanine; glycine and proline, compared to the proteome of the non-halophilic species (Tafer et al., 2019). The hypersaline conditions have lower water activities and higher salt concentrations, and cause the halophilic microorganisms to produce the essential industrial enzymes. Several studies on the halophilic hydrolases produced by the halophilic fungi such as the amylases; cellulases, lipases and proteases have been reported; however, fewer studies focused on the enzymes recovered from the obligate halophilic fungi (Chamekh et al., 2019; Ruginescu et al., 2020). Aspergillus sp. strain A4, Chaetomium sp. strain H1, P. vinaceum, Gracilibacillus halophilus, Wallemia sp. and Ustilago cynodontis demonstrated the highest enzymatic indexes (Chamekh et al., 2019). Different transporters were identified in the halophilic fungi to achieve ion gradient, including K⁺ efflux; K⁺ uptake, P-type ATPase and Na⁺ efflux (Gunde-Cimerman et al., 2018). This is the reason for survival of the halophilic fungi under the extreme salty conditions. Survival of the halophilic fungi under high salinity is mechanized at the cellular, genetic, enzyme and/or metabolic pathways, and is schematically presented in Fig. (1). In addition, list of the different halophilic fungi that were isolated from different extreme habitats and their salt tolerance concentrations are summarized in Table (3).

Fig. 1. Mechanisms of survival of the halophilic fungi under high salinity (Gunde-Cimerman et al., 2018; Pérez-Llano et al., 2020; Ruginescu et al., 2020)
Table 3: The halophilic and halotolerant fungi recovered from different sources based on their NaCl requirements

| S. No | Name of the halophilic\halotolerant fungi | Source                                   | NaCl (%)    | Reference                          |
|-------|------------------------------------------|------------------------------------------|-------------|------------------------------------|
| 1     | Gymnoascus halophilus, W allemia sp.      | Great Sebkha of Oran, Algeria            | 10 % 2.5-7.0 % | (Chamekh et al., 2019)            |
| 2     | A. salisburgensis                         | Salt Mine, Austria                       | 20 %        | (Tafer et al., 2019)              |
| 4     | A. glaucus, CCHA                          | Plant surface, China                     | 25 %        | (Qiu et al., 2020)                |
| 5     | A. sydowii, A. caesiellus                 | Sugarcane bagasse                        | 6 % 3 %     | (González-Abradelo et al., 2019)  |
| 6     | A. destruens                              | Canvass of an oil painting, Slovenia     | 12 %        | (González-Abradelo et al., 2019)  |
| 7     | W allemia ichthyophaga, Paranerita triangularis | Slovenian Sečovlje solar salterns     | 10-25 %     | (Primožič et al., 2019)           |
|       | Trinatostruma salinum, W allemia ichthyophaga, Hortaea werneckii, Phaeotheca triangularis | Solar salterns, Slovenia | 17 %        | (Primožič et al., 2019)           |

5. Applications of the halophilic and halotolerant fungi, and their future aspects

The different applications and future aspects of the halophilic and halotolerant fungi in the different sectors (i.e. health care, antimicrobial and anticancer activity, nanoparticle synthesis, enzyme production, genetics, bioremediation and other aspects) are show in Fig. (2).

5.1. Healthcare

Nowadays humans are creating lots of innovations in all the fields, which make the human's life better and/or enhance the quality of their health. Humans are fighting against different kinds of diseases (Stansberry et al., 2019). Traditionally, human diseases were treated based on the ancient healthcare systems of Ayurveda; Siddha, Unani and Chinese medicine; however, their modern medication system include; homeopathy, naturopathy and allopathy (Dhingra, 2020). Nevertheless, the current ways of living; eating habits and changes in ecosystem have created lot of destructions in the human lives, and allowed invasion of the pathogenic microbes as well. The previous study of Flandroy et al., (2018) revealed that the multidrug resistant pathogens are often heard and common ones to be observed now, which caused the human lives to be at greater risk and prone to diseases.
This has created difficulties among the researchers concerning detailed studies of the pathogenic microorganisms up to the genetic level. Accordingly, it has become very crucial to formulate new drugs that can change the scenario of drug resistance. It is to be noted that most of the drugs approved by the Food and Drug Administration (FDA) are made from microbes; including fungi and bacteria (Andrei et al., 2019). This provides insight for more exploration of the halophilic fungi that have wider applications in the field of health sector.

5.1.1. Anti-microbial activity

The exploitation of extremophiles is particularly important for the development of new molecules with potential applications in biomedicine (Giordano, 2020). Efforts are being primarily aimed at meeting the urgent health needs; particularly to those associated with two of the most serious global risks mainly; cancer and resistant bacteria (Aslam et al., 2018). Antibiotic resistance propagation is creating world threat towards the public health (Ben et al., 2019). During the continuous research on natural products; fungi provided the wider foundation for antimicrobials discovery. Ruginescu et al., (2020) reported that the halophilic and halotolerant fungal spp. that live in natural hypersaline environments do not require salt, as they can grow and adapt to wide range of salinities; ranging from freshwater to infused NaCl solutions. The halophilic fungi as sources of bioactive compounds with antimicrobial activities are presented in Table (4).
Table 4. The bioactive compounds produced by the halophilic fungi and their antimicrobial activities

| Source                                      | Fungi                                      | Affected pathogens                        | Bioactive compound                          | Reference                           |
|---------------------------------------------|--------------------------------------------|--------------------------------------------|---------------------------------------------|--------------------------------------|
| Abyssal marine sediment, Barents Sea.       | A. protuberus MUT 3638                     | S. aureus, K. pneumoniae, A. baumannii and B. metallica | Bisvertinolone                             | (Corral et al., 2018)                |
| Putian saltern of Fujian, China             | A. flocculosus PT05-1                      | E. aerogenes, P. aeruginosa, and C. albicans | Ergosteroids Pyrrole derivate               | (Corral et al., 2019)                |
| Putian saltern of Fujian, China             | A. terreus PT06-2                          | E. aerogenes, P. aeruginosa, and C. albicans | Terremide A, B Terrelactone A               | (Briard et al., 2019)                |
| Decay leaves of Avicennia marina, Red Sea   | Hortaea werneckii                          | Methicillin-resistant Staphylococcus aureus (MRSA), Campylobacter jejuni and Salmonella typhimurium | 4-Acetoxy-2-azetidinone, sec-Butyl nitrite and Fatty Acid Methyl Ester (FAME) | (Hodhod et al., 2020)                |
| Coast of Saudi Arabia                       |                                            |                                            |                                             |                                      |
| Soil Sample                                 | Streptomyces cuspidosporus strain SA4      | Escherichia coli, Klebsiella pneumonia, Staphylococcus aureus, S. typhi, Bacillus subtilis, Proteus vulgaris, Shigella flexineri, Candida albicans, and Fusarium sp. | 1,2-Benzenedicarboxylic acid, bis(2-Methylpropyl) ester compound | (Sholkamy et al., 2020)              |

5.1.2. Anticancer potential

A recent study conducted by Abdel-Razek et al., (2020) revealed that natural products are called as bioactive molecules, which include anticancer drugs produced by microorganisms. According to Pham et al., (2019), most of the well-established anticancer natural products have been obtained from plant cells, but microorganisms are also excellent alternatives because of these facts; 1) diversity of the microbial world, 2) ease of manipulation, and 3) ease of physiological screening to discover new natural
products with antitumor properties. In spite of the fact that bacterial cells communicate with the tumor cells in ways other than the metabolites do in laboratory; however, bacterial metabolites are believed to be the most reliable way to prevent cancer cells from surviving (Sedighi et al., 2019). Recently, more emphasis is focused on the extremophiles as new sources of the novel biomolecules (Corral et al., 2019). The halophilic and halotolerant microorganisms that live in hypersaline environments are thought to be reliable sources of antitumor metabolites. Several studies have reported the roles of metabolites of the halophilic microorganisms in treating cancer disease (Rani and Kalaiselvam, 2013; Corral et al., 2018; Ali et al., 2019; Ruginescu et al., 2020).

5.1.3. Role in nanoparticle synthesis

Nanotechnology has spread its roots in almost all the application fields. One of the innovations is nanoparticle (NP) synthesis, which are the smallest particles; whose size range from 1-100 nm (Rajput, 2017). These NP are synthesized through three methods namely; physical, chemical and green synthesis, depending on their fields of application as demonstrated in Fig. (3).

![Fig. 3. Different methods used for synthesis of the nanoparticles (NPs) (Ijaz et al., 2020; Salem and Fouda, 2021)
Green synthesis refers to the production of NPs from microbes (Salem and Fouda, 2021). Nanoparticles are widely used in different fields including; textile, healthcare, food, agriculture, electronics, environment, renewable energy and various manufacturing processes (Jeevanandam et al., 2018). With respect to healthcare, many applications primarily drug delivery systems; are being reported for the NPs, as this method does not harm any tissue or organ while delivering the drug to the body (Chauhan et al., 2020). The NPs produced from the halophilic fungi also act as inhibitory agents against wide range of microbes, and are known also to have potent antimicrobial activities (Wang et al., 2017). The process for green synthesis of the NPs is shown in Fig. (4).

Fig. 4. Green synthesis of the NPs using the halophilic fungi (Huston et al., 2021)

5.2. Biotechnological applications (Enzymes production)

The extremophilic fungi are diverse groups of microbes with wide ranges of adaptation properties; genetic diversities and metabolic mechanisms that allow them to survive under high-salt containing environments. These fungi have numerous applications in the field of biotechnology; medicine, agriculture, genetics and others. Different applications of the halophilic and/or the halotolerant fungi have been developed (Satyanarayana et al., 2005); mainly the
ability of these fungi to produce numerous enzymes. During the study of Chamekh et al., (2019), the halophilic fungi were isolated from Sebkha in Oran, Algeria, and their enzymatic activities were investigated. It was recorded that they could produce different types of enzymes including; lipases, amylases, proteases and cellulases; in presence of NaCl-rich medium. Production of the halotolerant protease by the halophilic fungus A. flavus can be applied in several industrial processes; as in normal cases, the salty solutions are used to inhibit activity of the normal proteases (Razzaq et al., 2019). Enzyme activity of α-amylase produced by the halophilic fungus Engyodontium album is found to increase with increasing NaCl concentration, and it has lot of applications in food; pharmaceutical and the detergent industries (Elyasi Far et al., 2020). A. flavus KUB2 produces the halophilic cellulases which have wide commercial applications (Namnuch et al., 2021). The different species of halophilic fungi associated with the production of specific enzymes, and their fields of applications are summarized in Table. (5).

Table 5. The different species of halophilic fungi characterized by the production of various enzymes

| Halophilic fungi | Source | Enzymatic activity | References |
|------------------|--------|--------------------|------------|
| A. subramanianii A2 | Great Sebkha of Oran | Lipase, Amylase, Protease, Cellulase | (Chamekh et al., 2019) |
| A. terreus S11 | Great Sebkha of Oran | Lipase, Cellulase | (Chamekh et al., 2019) |
| P. mariae crucis S19 | Great Sebkha of Oran | Amylase, Protease, Cellulase | (Chamekh et al., 2019) |
| A. flavus KUB2 | Soil with decomposed plant materials and wood decayed samples | Cellulase, xylanase | (Namnuch et al., 2021) |
| Triramostroma salinum EXF-295, Wallemia ichthyophaga EXF-5676, Hortaea wernecki EXF-225, Phaeotheca triangularis EXF-206 | Solar salterns | α-amylase, Protease, β-glucosidase | (Primožič et al., 2019) |
| A. flavus | Suez Gulf | Chitinase | (Beltagy et al., 2018) |
5.3. Agriculture (Genetic)

The halophilic fungi help the humans to understand how survival is possible at extreme conditions by studying their biogeochemical cycles, which includes sulfur; nitrogen, carbon, and phosphorous that operate under extreme conditions (Martínez-Espinosa, 2020). Transcriptomics research is extremely beneficial in understanding gene expression and repression in the living organism. *A. salisburgensis*, which is a halophilic fungus compared to the halotolerant fungus *A. sclerotialis* showed difference in the transport-related genes (Tafer et al., 2019). Moreover, studying of *A. sydowii* under different salinity conditions showed expression profiles on the basis of stress-related genes; with an increase in the expression of the solute transporter coding gene (Pérez-Llano et al., 2020). The comparative studies conducted among *Wallemia ichthyophaga*, *Hortaea werneckii* and *Aureobasidium pullulans* demonstrated higher salinity tolerance, which was correlated with the superoxide dismutase, catalase and peroxiredoxin coding genes, also known as the oxidative stress response genes; responsible for both antioxidant activity and salt tolerance (Gostinčar and Gunde-Cimerman, 2018).

The increasing global problem of the agricultural salinization has put forward the halotolerant and halophilic fungi as emerging sources of target genes, which can be used to increase salt tolerance in plants at the genetic level (Egamberdieva et al., 2019). Salt tolerance mechanism in plants is beneficial; as it can protects the plants from being destroyed with the increasing soil pollution (Kamran et al., 2019). Recently, Gupta et al., (2021) reported that modifications in the model microorganisms can also be carried out, which show symbiotic association with the plants and indirectly help them to resist high salt concentrations.

5.4. Environment (Bioremediation)

Bioremediation is the process of removing pollutants from the environment through the use of living organisms; primarily the microbes (Abatenh et al., 2017). Although the halophilic microorganisms have been studied as promising bioscience agents used for the degradation of pollutants at high salt concentrations, however their bioremediation potentials still remain unclear (González-Abradelo et al., 2019). Pollutants are present in almost every ecosystem (air, water and land), and their presence is becoming harmful to the communities that live in these systems. It is necessary to remove the harmful pollutants from the environment, which can be accomplished through bioremediation (Liu et al., 2017b). Due to robustness of the extremophilic halophilic and halotolerant fungi, they have important roles in bioremediation applications even under harsh conditions.

According to Briffa et al., (2020), heavy metals are part of the pollution in the marine environment and they become difficult to remove. Fungi; with their potentials to remediate the soil polluted by heavy metals are generally adaptive to the polluted environment. Jin et al., (2021) proposed that these fungi might have evolved mechanisms to escape the damage that heavy metals have created to them. *A. flavus*, *A. restrictus* and *Sterigmatomyces halophilus* are halophilic fungi that have metal degradation potencies; with their abilities to ingest Copper (Cu) metal (Bhattacharjee and Goswami, 2018). Meanwhile, *A. flavus* and *S. halophilus* have the abilities to degrade cadmium and Zinc; those chemicals are also degraded by *A. gracilis* and *S. halophilus* (Kalpana et al., 2018).

Agricultural lands have become polluted due to the excessive usage of pesticides; herbicides and the other harmful chemicals. These pollutants have completely reduced the ability of soil to provide beneficial components for growth of the plants, due to accumulation of the chemicals inland (Meena et al., 2020). Huge quantities of petroleum pollutants enter
the environment causing serious degradations of the land and the water ecosystems (Fowzia and Fakhruddin, 2018). Microbial biodegradation of petroleum hydrocarbon pollutants has long been considered as eco-friendly; cost-effective and efficient biological treatment; however, their functionalities are reduced at extreme environments. So, there is a great need for enzymes and/or compounds which can operate under extreme conditions (Li et al., 2019). Enzymes such as lipase; amylase, protease, cellulase, β-glucosidase and chitinase are produced by the different halophilic fungi, which thus have greater applications during the process of bioremediation (Beltagy et al., 2018; Chamekh et al., 2019; Primožič et al., 2019; Namnuch et al., 2021). The halophilic fungi with their sources and produced enzymes are presented in Table (5).

5.5. Other applications (Cosmetology/ Food/ Textile)

Colors are having high demands in the fields of biotechnology related to food; textiles, medicine and cosmetics (Sajid and Akbar, 2018). Fungi are microbes that can create powerful pigments, which can be used as dyes or food colorants in the form of secondary metabolites. This application is possible with the help of pigments extracted from the halophilic and the halotolerant fungi. These pigments are compounds which absorb the light of specific wavelength at the visible region (Heer and Sharma, 2017).

Fungi are known to produce diverse range of pigments, including melanin; anthraquinones, hydroxyantraquinones, azaphilones, carotenoids, oxopolyene, quinones and naphthoquinone (Kalra et al., 2020). Melanin pigment isolated from the halophilic fungus Hortaea wernecki has a cosmetic role (Sajid and Akbar, 2018), and is used also in the textile as well as in the food industries (Heer and Sharma, 2017). Talaromyces verruculosus produces red pigment (Chadni et al., 2017), whereas Trypethelium eluteriae produces Trypethelonamide A as red pigment, and 5-hydroxytrypethelone; (--)-trypethelone, (+)-trypethelone, (+)-8-hydroxy-7-methoxytrypethelone as dark violet-red pigments (Basnet et al., 2019). The marine fungus Talaromyces albobiverticillius 30548 also produces a red pigment (Venkatachalam et al., 2019). Isolation of the bioactive molecule Funiculosone from the endolichenic fungus named Talaromyces funiculosus yielded three compounds, one of them is ravenelin; a yellow colored homogeneous powder with good antimicrobial activity, thus making it beneficial in the pharmaceutical and food industries (Padhi et al., 2019). Penicillium sp. (GBPI_P155) isolated from the Himalayan region is found to produce an orange pigment, which is a derivative of the carotenoids (Pandey et al., 2018). Similarly, the fungus Monascus ruber M7 has the ability to produce Azaphilone pigment, which is orange; red or yellow in color (Chen et al., 2017). In considering the overall benefits of fungal diversity; fungi are regarded as the cell factories for pigments production, where researchers can experiment with their functionalities (Kalra et al., 2020).

Conclusion

This study discussed living of the halophilic and the halotolerant fungi under the harsh environmental conditions, and began with the basic understanding of the fungal habitats. Based on these fungal nutrient requirements, they are considered to be extremophiles. They are halophilic in nature, and require NaCl for their growth and survival. They exhibit different mechanisms to survive under extreme conditions. Furthermore, the enzymes isolated from these fungi have higher activities under high salt concentrations, and have wide range of industrial applications. Synthesis of the bioactive compounds and their inhibitory activities make the halophilic fungi blessing to the health care industry in fighting against the multidrug-resistant pathogens. Synthesis of nanoparticle is also the greatest breakthrough; because they have wide variety of applications, and play important roles in the drug delivery systems. In addition, the halophilic fungi are also very essential in the field of cosmetic industry. In conclusion, many fungi exist in different environments, but still remain...
unexplored. Accordingly, there is a need for further researches to discover and isolate the novel halophilic and halotolerant fungi, which have more potential in helping the mankind with their diverse products; beneficial mainly toward the human health.

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**Conflict of interest**

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