Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/19624
DOI URL: http://dx.doi.org/10.21474/IJAR01/19624

RESEARCH ARTICLE

HALOPHILIC ASPERGILLUS SPECIES IN EXTREME ENVIRONMENTS: PHYSIOLOGY, ADAPTATIONS, AND APPLICATIONS

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Manuscript Info

Manuscript History
Received: 05 August 2024
Final Accepted: 09 September 2024
Published: October 2024

Key words:-
Halophiles, Mycobiota, Mycoremediation

Abstract

Salt is essential for growth at certain limits, but life dwelling in harsh, salty environments are the halophiles. Studies on the halophilic bacteria, archaea, and fungi are reported around different locations, but the fungus Aspergillus species is a predominant halophilic eukaryote reported in various research works. They have been reported from an environment with high salt concentrations. Halophilic Aspergillus species grow better in harsh conditions and have an exciting opportunity for research and application ahead of them. Their potential in biotechnology, together with their special capacity for adaptation to harsh settings, makes them precious in many sectors from environmental science, to biotechnology, and even in bioremediation settings. Therefore, this work review the physiology and unique adaptations of halophilic Aspergillus species in extreme environments, biomolecule produces and their applications in different areas and future prospects.

Introduction:-

Ascomycetae is a group of mycobiota containing the Aspergillus genus. It dwells in hypersaline environments and is considered a halotolerant halophilic filamentous fungus.

Aspergillus species arediscovered in hypersaline environments and are classified as moderate to extremely halotolerant and halophilic fungi. They are being identified as new and uncommon species, including those that were previously known. (Gunde-Cimerman & Zalar, 2014).

The halophilic Aspergillus species bearing conidiophores are propagated asexually. Halotolerant Aspergillus contains a well-developed cell wall, septate hyphae, nucleus, smaller vacuoles, thick granular cytoplasm, and large mitochondria of various shapes. The cytoplasmic membrane is undulated in tandem with the hyphal wall, and lipid globules and melanin granules develop at the front of the cell membrane. Many lysosomes emerged in the hyphal cytoplasm(EL-MeLEigy MA, n.d.). According to the study, the Aspergillus species has larger conidia, can tolerate dry circumstances, and can endure high salt. The thicker hyphae of halophilic Aspergillus maintain the cell's ionic balance also reported(Jiménez-Gómez et al., 2022).

The halophilic Aspergillus species is commonly found in soil, decaying organic matter, and indoor environments. These filamentous fungi are found in the different geographical regions of around world, for eg. fungi from the great Sebkha of Oran, Algeria(Chamekh et al., 2019), Miani-Hor Mangrove Forest Soil from Pakistan(Khan et al., 2020),

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Gulf sediment located in NorthAmerica(González-Martínez et al., 2017), Bonna sediment locates in New England(Corral et al., 2018a), flora of Salt mines and salterns in Jilin, China(Qiu et al., 2020). The halophiles live in association with a plant growing around salt mines, the Medicago sativa L. Plant (González-Abradelo et al., 2019a)and fibrous waste material of (Liu et al., 2017).

This salt-loving species is divided into the ranges of salt concentrations found naturally and in artificial environments. Dead sea marine environments and salt lakes contain moderate to extreme salt concentrations(Chamekh et al., 2019; Lee, 2013). They can grow well in various substrates and to a various environmental conditions, such as different temperatures, low water conditions, pH levels, and different salt concentrations (Pitocchi et al., 2020). The halophiles are categorized into moderate and extreme salt-loving species.The species sustain and adapt themselves to environments or niches that contain moderate to extreme salt extents.

The majority of halophilic fungi are included in Ascomycota, of which the most important species is Aspergillus species. The exact classification of the Halophilic Aspergillus genus may vary depending on the specific species and recent phylogenetic analyses. But, in many studies, different species of AspergilluslikeA. flavus, A. niger, A. terrus, A. versicolor, A. restricuts, A.glaucus, A. chevalieri, A. alternate, A. destruens, A. loretoensis, A. atacamensis, A. salisburgensis, A. sclerotialis, A. Montevidenis, A. cristatus, A. ruber (previously Eurotium rubrum), A. Subalbidus, A. candidus, (Gunde-Cimerman&Zalar, 2014), Aspergillusniger, Aspergillusnomius, Aspergillus sp. SFB81and many more species were reported as halophiles in different studies(Wingfield et al., 2023).

Molecular adaptations:

Extremolyets and extremozymes are produced by halophilic fungi in extreme environmental conditions to maintain the osmotic stress (Raddadi et al., 2015).

Exposure to high salinity causes fungi to experience osmotic stress and ionic stress. In high salinity, halophilic fungi adapt mechanisms like salt in, accumulation of organic osmolytes, low salt, salt out, and maintaining the proper membrane fluidity(Pérez-Llano et al., 2020a).

In high osmolarity, some fungi can prevent water loss by accumulating K+ ions in their cells while excluding Na+ ions (PlemenitaÅ¡ et al., 2014).

At molecular level mechanisms, the proteins in the plasma membrane contain acidic amino acids at the surface. Proteins make a protective barrier with the help of water, remain active in ionic stress, and prevent dehydration and precipitation of the molecules.

In one of the studies of halophiles A. sydowii, Yordanis Pérez-Llano et al. mentioned the balance of ions during osmotic stress is independent of osmotic conditions.

Organic osmolytes or compatible solutes are produced by the genus Aspergillus inside the cell but are released extracellularly, and they are extractable. The osmolytes that maintain the osmotic balance and do not alter the activity of enzymes are polyols, noncharged solutes (sucrose, trehalose), anionic solutes (β-glutamate, hydroxybutyrate), zwitterionic solutes (betaine, ectoine), and dimethylsulfoniopropionate. In Aspergillus niger, glycerol, erythritol, mannitol, and trehalose have been reported, and glycerol is the only osmolyte reported in most of the hypersalinity(Pérez-Llano et al., 2020b).Some fungi can accumulate osmolytes like polyols, sugars, and amino acids as s compatible organic solutes (Roberts, 2005).

Halophiles can cause structural modification in cell envelope due to the presence of pigments and/or hydrophobins (Pérez-Llano Y, Gostinčar C).

Metabolic Adaptation:

The metabolic adaptation of A. sydowii isconsiderd as a model for the study of adaptations of halophilic Aspergillusspecies, as reported by Jimenez Gomez et. al. In the study, at saturated NaCl conditions, glutamate presence was reported and some amino acids like serine, glycine, alanine, etc levels couldn’t change while sulphur containing amino acids like methionine, cysteineand also proline were not found. Tridecanoic acid and palmitic acid were reported in both conditions of A. sydowii found in mycelia. Unsaturated fatty acids with an 18-carbon chain reported at the maximum level for supporting fungal growth in hypersaline growth. In the saturated NaCl concentration, glucanosyltransferase-domain-containing protein and β-1,3 glucan biosynthesis were found. In one of the study movement of glucose, amino acids, and Na+ facilitate by the membrane protein. (Jiménez-Gómez et al., 2022).

Enzymes by Halophilic Aspergillus species: (Hydrolases, Oxidoreductase)
Halophilic Aspergillus species produce extracellular biocatalysts under osmotic and ionic stress.

Hydrolases involved in the metabolic pathway use water to break down the molecules, and oxidoreductases oxidize and reduce substrates by transferring electrons from one substrate to the other.

Hydrolases are water-soluble which have polythermophilicity, and can maintain high stability(Datta et al., 2010; Primožič et al., 2019; Ruginescu et al., 2020; Yin et al., 2015; Zain Ul Arifeen & Liu, 2018). This halophilic filamentous fungus produces different extracellular enzymes, has industrial uses, and can be easily extracted(Datta et al., 2010; Fuciños et al., 2012; Primožič et al., 2019).

An extracellular alginate lyasehave a potential application such as in the biomedical sector generated by Aspergillusoryzae(Singh et al., 2011).

Halophilic fungi produces hydrolases like amylase, lipase, cellulase, protease, xylanase, pectinase, and others(Ruginescu et al., 2020; Zhang et al., 2018).

These enzymes are use in the industries for biofuel production, bioremediation, food, cosmetics, detergent, and pharmaceutical processes, and in various sectors(A. Ali Imran, 2014; Amoozegar et al., 2019; González-Abradelo et al., 2019b; Mudau & Setati, 2006).

Halophilic Aspergillus species also produces enzymes oxidoreductases (manganese peroxidases, lignin peroxidases, laccases) which can degrade lignin.

These lignolytic enzymes decolorize dyes, repair coloured effluents, decompose other organic contaminants, and help with bioremediation. (Bonugli-Santos et al., 2012).

Table 1:- Different enzymes from halophilic Aspergillus species and their applications.

Enzymes	Aspergillus species	Industrial applications	References
β-galactosidase	Aspergillus tubingensis GR1	Many Industrial and Medical Applications	(Raol et al., 2015)
Cellulase	Aspergillus flavus, Aspergillus restrictus, A. subramanianii A2, A. terreus S11, and A. flavus KUB2	Biofuel Production	(A. Ali Imran, 2014; Chamekh et al., 2019; Namnuch et al., 2021)
Amylase	Aspergillus gracilis, Aspergillus penicillioides, **Aspergillus penicillioides** TISTR3639, **Aspergillus gracilis** TISTR 3638, A. subramanianii A2	Saline Waste Water treatment	(A. Ali Imran, 2014; I. Ali et al., 2014a, 2015; Namnuch et al., 2021)
Lipase	Aspergillus gracillus, Aspergillus restrictus, A. subramanianii A2, A. terreus S11	bioremediation of saline oil spills	(A. Ali Imran, 2014; Namnuch et al., 2021) 39
Xylanase	A. gracilis Aspergillus sp. Av10, Aspergillussp.Sh 86, A. niger G 2-11, A. niger S87, A. niger K6-11, and A. flavus KUB2	Food industry, bakery, paper and pulppharmaceutical, inbio-refinery, andtextile.	(A. Ali Imran, 2014; Kutateladze, 2009; Phuyal et al., 2023)
Protease	Aspergillus restrictus, A. subramanianii A2	fish sauce production	(A. Ali Imran, 2014; Namnuch et al., 2021)
β-glucosidase	Aspergillus sydowii BTMFS55	food and pharmaceutical	(Madhu et al., 2009)

		industry	
Pectinase	Aspergillussp.Sh 86, A. niger G 2-11, Aspergillusniger S87, Aspergillus sp. Av 10,Aspergillusniger K6-11.	Fruit ripening	(Kutateladze, 2009)
Esterase	A. sydowii EXF-12860, A.destruens EXF-10411	Bioremediation	(González-Abradelo et al., 2019a)
Chitinase	A. flavus	Important food and pharmaceutical industries, antimicrobial agents, elicitors, lysozyme inducers, and immune enhancers	(Beltagy et al., 2018; Pradeep Kumar, 2021)
Alginate lyase	A. oryzae	Biomedical industry	(Singh et al., 2011)
Collagenase	Aspergillus oryzae	Healthcare	(Chamekh et al., 2019; Moubasher, 2018)
Other enzyme			
Lignin Peroxidase, Manganese peroxidase	Aspergillus scelrotiorumCBMAI 849	decolorization of dyes, remove colour from waste water, breakdown of other organic pollutants, and bioremediation	(Bonugli-Santos et al., 2010)
Peroxidase, laccase, Catalase, glutathione peroxidase and superoxide dismutase	Aspergillus sydowii EXF-12860,		(González-Abradelo et al., 2019a; Jiménez-Gómez et al., 2020)
Peroxidase, laccase	Aspergillus destruens EXF-10411		(González-Abradelo et al., 2019a)

Bioactive compounds by halophilic Aspergillus species: (Antimicrobials, anticancer and Antioxidants)

The halophilic Aspergillus, the dominant genus, is living in man-made and naturally found hypersalinity. They are extraordinary producers of diverse bioactive compounds called secondary metabolites or natural products(Corral et al., 2018b)(44)(Corral et al., 2018b). They produce bioactive compounds like antimicrobials, anticancer, and antioxidants used in the case of bacterial infections, cancer treatments, and food prevention.

Halophiles produce bioactive compounds like bisvertinolone, 2-hydroxycircumdatin C, ergosterol, etc. and some novel compounds (Corral et al., 2018b; Zheng et al., 2013) (Table 2).

Halophilic fungus produces secondary metabolites that can be used for survival, growth, and communication, and they have industrial and clinical (Cui et al., 2009; Xiao et al., 2013).

The halophilic Aspergillus species can also produce a natural product that is effective against human and plant pathogens such as bacterial and fungal infections (Table 2).

Some of the secondary metabolites form by halophilic Aspergillus species not yet been identified.

Bioremediation: recycling of environmental pollutants

Copper, silver, zinc, nickel, lead, mercury, arsenic, cadmium, chromium, and selenium are a few of the heavy metals that are harmful to life at very low concentrations (Han, 2002). Most industrial processes associated with metal fabrication, leather tanning, and other landfill hazardous waste sites also produce leachates. Leachates are the main sources of heavy metals, which accumulate in nature and are not converted into degradable form(Reed, 1994; Schalscha, 1998).Bioremediation is a cutting-edge, environmentally friendly, and rapidly expanding technology that makes use of the capacity of bacteria, fungi, algae, or plants to extract heavy metals from contaminated places and either reduce them into less dangerous forms or recover them(Fenner, 2013).Amongst all biological forms, the fungus is the most promising microlife and gives the best results in bioremediations of recalcitrant compounds(Vijayaraghavan, 2006a). Therefore, mycoremediation, or the use of fungus, is a dependable and effective method, as they are natural decomposers and produce several extracellular oxidoreductase enzymes(Bonugli-Santos et al., 2010; González-Abradelo et al., 2019b).

Table 2:- List of Bioactive compounds produces by halophilic Aspergillus species.

Activity	Species	Compounds	Refrences
Antimicrobial	Aspergillus protuberus MUT 3638	Bisvertinolone	(Corral et al., 2018b)
	A.gracilis, A.penicillioids, andA. flavus	crudeproduct	(A. Ali Imran, 2014)
	Aspergillus flocculosus PT05-1	Ergosteroids, Pyrrole derivatives:	(Zheng et al., 2013)
	Aspergillus terreus PT06-2	Terremide A & B, Terrelactone A	(Briard et al., 2019; Wang et al., 2011)
	Aspergillus terreus Tsp22	Crude Product	(Lebogang, n.d.)
Antioxidant	A. ochraceus EN31	2-hydroxycircumdatin C	(Cui et al., 2009)
	A. wentii EN-48	Methyl 4-(3,4-dihyroxybenzamido) butanoate, 5-O-methylsulochine, 4-(3,4-dihyrdroxybenzamido) butanoic acid	(Li et al., 2014)
Anticancer	Aspergillus sp. Nov. F1	Ergoserol, Rosellichalasin, Cytochalasin E	(Xiao et al., 2013)
	Aspergillus flocculosus PT05-1	New ergosterol derivative, 7-norergosterolide, 3b-hydroxyergosta-8, 24(28)-dien-7-one.	(Zheng et al., 2013)

The polyextremophilic α-amylase obtained from halophilic Aspergillus gracilis TISTR 3638 can be effectively applied for saline wastewater remediation in mild acidic and temperature conditions and at lower water activity(I. Ali et al., 2014b). Aspergillus species like A. tubingensis GR1 isolate efficiently produce β-galactosidase by using agro-based waste, largely a part of unused crop residues. These halophiles can solve the reuse of agro-based waste for commercial purposes(Raol et al., 2015).Halophilic mycobiota like A. sydowii and A. destruens, due to mycotreatment, biodegrade and adsorb the xenobiotic compound polycyclic aromatic hydrocarbons (PAH) and pharmaceutical compounds (PhC) from saline biorefinery wastewater(González-Abradelo et al., 2019b).A marine fungus, A. sclerotiorum CBMAI849, reported that recalcitrant molecules like pyrene and benzopyrene were efficiently metabolized, and it shows the Aspergillus species bioremediate the recalcitrant compound in saline conditions(Passarini et al., 2011). In the study of biosorption by obligate halophilic fungi using Aspergillus flavus, Aspergillus gracilis, Aspergillus penicillioides (sp. 1), Aspergillus penicillioides (sp. 2), and Aspergillus restrictus, amongst them A. flavus showed 86% efficiency of adsorption(Bano et al., 2018).

Conclusion:-

Halophilic and halotolerant fungi are the mycobiota living in harsh salinity conditions where many species exist. The present study aims to explore the dominant halophilic Aspergillus species that inhabit artificial and natural salty environments. Halophilic Aspergillus species developed adaptive mechanisms at molecular and metabolic levels, and more studies on adaptation mechanisms species-wise are needed. Halophilic Aspergillus species produce different biomolecules which are unique and helpful in different biotechnology and healthcare areas. The halophilic Aspergillus species produce biocompounds that are helpful in the recycling of environmental pollutants. To the best of our knowledge study on bioremediation of arid and semiarid regions has not been done so far and there is need to remediate the soil of this regions using halophilic fungi or their biocompounds. Therefore, future research on the isolation of more halophilic Aspergillus species and searching for new industrial potential biomolecules have to be explored.

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