Bulletin of Pure and Applied Sciences.
Botany, Vol.44 B, No.2.
July-December 2025: P. 179-189
Review Article

Print version ISSN 0970 4612
Online version ISSN 2320 3196
Available online at www.bpasjournals.com

Acclimatization of Cryptogams: A Critical Review towards Finding the Research Gap for Their Conservation

[1]Subir Samanta, [2]Sandipan Pal, [3]Sk Md Ismail Al Amin, [4]Mukunda Dey, [5]Dr. Aveek Samanta*

Author's Affiliation
[1, 5] Department of Botany, Prabhat Kumar College, Contai-721404, West Bengal, India.
[2]Department of Environmental Science, Aghorekamini Prakashchandra Mahavidyalaya, Subhasnagar, Bengai, Hooghly-712 611, West Bengal, India.
[3]Department of Botany, Government General Degree College, Telipukur, Tilaboni Mahishamura, Keshiary, Paschim Medinipur- 721135, West Bengal, India.
[4]Department of Geography, Aghorekamini Prakashchandra Mahavidyalaya, Subhasnagar, Bengai, Hooghly-712 611, West Bengal, India.

***Corresponding Author:**
Dr. Aveek Samanta
Department of Botany, Prabhat Kumar College, Contai, West Bengal- 721404, India
E-mail: aveekbot@gmail.com

Keywords:
Adaptation, Conservation, Cryptogams, Diversity, Ecological role, Survival

Received on 10.08.2025
Revised on 19.09.2025
Accepted on 11.11.2025

Abstract
This current review sheds light on the physiological, biochemical and molecular mechanisms that allow cryptogams to acclimatize and adapt to environmental changes, highlighting their potential for conservation. The paper evaluates how cryptogams respond to simulated natural conditions. Our findings reveal that these organisms use a combination of rapid acclimatization strategies, such as water regulation and pigment biosynthesis, and long-term genetic adaptations, including the development of antifreeze proteins and drought-resistant structures. These works emphasize the importance of combining technological and ecological approaches for effective cryptogam conservation, particularly through methods like artificial cultivation, cryopreservation, and habitat restoration. The research underscores the ecological significance and environmental sensitivity of cryptogams, stressing the need for targeted conservation efforts to preserve biodiversity and ecosystem stability in a changing climate. Ultimately, this work provides a deeper understanding of cryptogam resilience and offers a scientific basis for developing sustainable global preservation initiatives.

How to cite this article: Samanta S, Pal S, Ismail SM, Dey, M and Samanta, A. (2025). Acclimatization of cryptogams: a critical review towards finding the research gap for their conservation. *Bulletin of Pure and Applied Sciences-Botany*, 44B (2), 179-189.

INTRODUCTION

The word "cryptogams" originates from the Greek terms kryptos (hidden) and gamos (marriage), referring to their concealed reproduction. The cryptogams do not produce flowers or seeds and hence hey are also called as non-flowering or seedless plants. They represent a diverse assemblage of spore-producing organisms encompassing thallophyte (algae, fungi, lichens), bryophytes (mosses, liverworts, and hornworts) and pteridophytes (ferns and fern allies) (Varela et al., 2021). Unlike angiosperms, cryptogams exhibit simpler anatomical structures, making them excellent model organisms for studying fundamental biological processes (Salinas et al., 2022). Cryptogams are divided into three sub-kingdoms: Thallophyta, Bryophyta, and Pteridophyta. Cryptogams play an essential role in maintaining ecosystem stability and biodiversity despite often being overlooked in conservation efforts (Mohan et al., 2017). Cryptogams rank among the earliest terrestrial plants, emerged about 400 million years ago. Their evolutionary history offers valuable insights into the transition of plants from aquatic to terrestrial environments (Strother, 2000). The relatively simple genomes of various cryptogams, combined with advanced genomic and transcriptomic techniques, have enabled researchers to examine the molecular basis of these evolutionary transitions (Nelsen et al., 2020).

Cryptogams share several interesting characteristics. Spores serve as their reproductive cells, and they require moisture for germination. The absence of vascular tissues makes them depend on external water sources. Their ecological preferences are diverse; algae thrive in aquatic environments, while mosses and ferns flourish in moist soils (Varela et al., 2021). These organisms are remarkably resilient in harsh environments, making them essential for maintaining biodiversity and supporting ecosystem function. Due to their structural limitations, cryptogams cannot achieve the same vertical growth as seen in vascular plants. Nevertheless, they perform vital ecological functions including carbon storage, soil stabilization and rainwater absorption (Salinas et al., 2022).

BACKGROUND AND CONTEXT

Acclimatization is the process by which an individual organism adapts to alterations in its surroundings (changes in altitude, temperature, humidity, photoperiod and pH) enabling it to sustain fitness across varied environmental conditions (Hicklenton et al., 1976). Acclimatization occurs through two distinct temporal pathways: a rapid phase, spanning from hours to weeks, and a gradual phase that unfolds over the organism's lifespan (Chapman, 2008). This could be a specific event (for instance, when climbers adapt to altitude over several hours or days) or might signify a segment of a recurring pattern, like a mammal losing its thick winter fur for a lighter summer coat (Singh et al., 2022).

Organisms can modify their morphological, behavioral, physical, and/or biochemical characteristics in response to environmental changes. Although the ability to adapt to new environments has been extensively recorded for numerous species, scientists remain unaware of the mechanisms and reasons behind how and why organisms acclimate as they do (Lõhmus et al., 2009). Since researchers initially started examining acclimation, the prevailing hypothesis has been that all acclimation aims to improve the performance of the organism (Kluge et al., 2000).

For cryptogams acclimatization is important for enhance their ability to establish in a new location, specifically in ex situ conservation settings where the artificial conditions might be significantly different from their native habitats (Nygaard, 1975). In the view of environmental disturbance, acclimatization mechanisms like adjusting to the photosynthetic activity, modification of reproductive cycles and development of water retention determine the survival of the species (Jung et al., 2024).

Cryptogams play a crucial role in the functioning of ecosystems, providing essential ecosystem services that all of society relies on (Mohan et al., 2017). These plants function as the primary ecological pioneers, helping to establish vegetation in the Barren landscapes by breaking the rock surfaces and initiating soil formation. Their mat-like dense structures prevent soil erosion and contribute towards the improvement in nutrient cycling, making them specifically important in maintaining fragile environments like wetlands or mountaineering regions (Bezbarua et al., 2024). Cryptogams function as the primary reservoirs of moisture, storing and absorbing the water. Thus, they support the surrounding flora and fauna by regulating the temperature and local humidity, building microhabitats that enable the sustenance of distinct species, including insects, microorganisms, and small vertebrates (Thakur et al., 2020). They establish symbiotic connections with most vascular plants and serve as a crucial food supply for numerous other creatures, like Land Snails. They capture carbon and promote carbon storage within the soil (figure 1). They also shield seeds in the soil from light rain and unsuccessful germination. Only substantial rainfall breaks through the surface crust to access seeds and promote germination with sufficient soil moisture or the seedling to thrive (Gaskin et al., 2001)

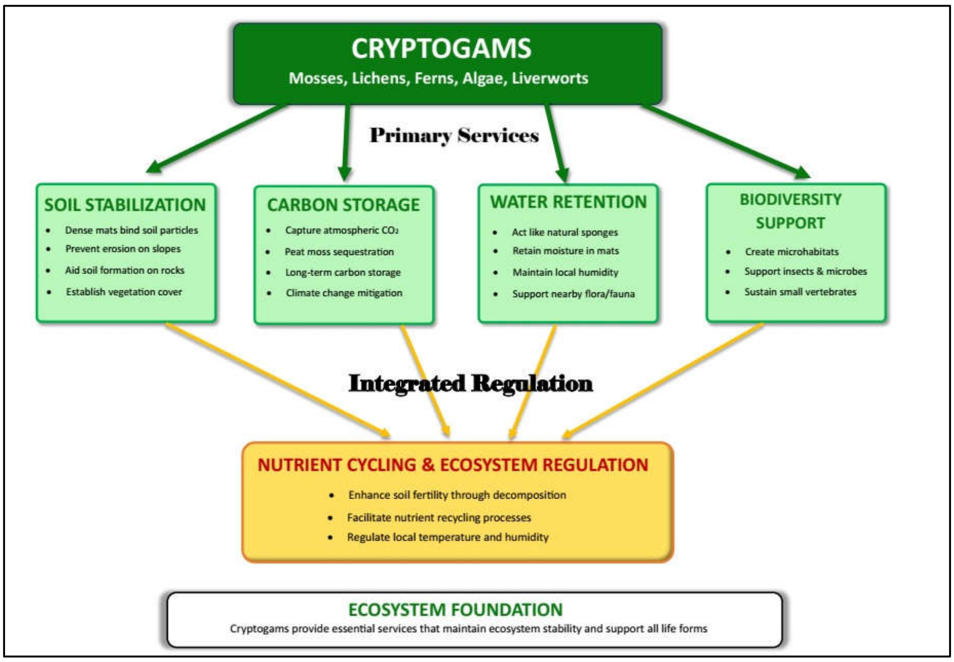

Figure 1: Flow diagram of ecological role of cryptogams

Irrespective of their ecological importance, the cryptogams represent one of the least understood groups among all organisms (Dudani et al., 2017). Cryptogams face extensive conservation challenges because of habitat destruction, pollution and climate change. Climate change also presents an extensive threat because increasing temperatures and changes in precipitation patterns disrupt their delicate water balance, leading to population decline and However, cryptogam still receives limited attention compared to larger vascular species. The conservation of cryptogams depends on implementation of policies which not only degradation (Li et al., 2004). They are dependent on immediate environmental conditions, which make them specifically vulnerable to ecological changes (Cornelissen et al., 2007).Unlike higher plants the conservation of cryptogams demands special strategies as opined by the experts. Inclusion of cryptogams in biodiversity assessments and restoration (Dilrukshi et. al. 2024).

protect them but also conserves their microenvironment by enhancing protection zones and encouraging community involvement (Baniya, 2010, Dudani et al., 2011).

Acclimatization plays a critical role in the survival of cryptogams, enabling them to adjust to environmental changes and maintain their ecological functions.

PRESENT THREAT TO CRYPTOGAMS

Cryptogams serve as the fundamental components of all types of ecosystems on Earth and are an integral aspect of biodiversity (Deori et al., 2022). They create the ideal environment for the development of higher plants, insects, and animals, which serves as essential components of the ecosystem services like climate regulation, environmental assessment, water purification, nutrient cycling, habitat modification, and more (Singh et al., 2018). Despite this, many cryptogams hold socio-economic significance and serve various uses, including food, fodder, vegetables, bio-fertilizers, traditional medicine, agriculture, horticulture, and various industries.

Recent estimates indicate that Indian regions host a total of 50,012 taxa from the plant kingdom. Among them, approximately 62.4% (31,212 taxa) are classified as cryptogams, while 37.6% (18,800 taxa) are associated with angiosperms. Interestingly, numerous hilly regions and remote places remain unexamined regarding cryptogams (Singh et al., 2018). The situation regarding cryptogam conservation research in India is quite unsatisfactory when considering the country's extensive geographical expanse and the numerous species documented in this category of plants (Thakur et al., 2020). Between 2000 and 2005, merely around. 4% of articles in top conservation journals focused on cryptogams (Hylander et al., 2007).

The convention highlights the importance of recording a variety of organismic diversity, along with its sustainable use and monitoring the effectiveness of the implemented conservation actions. Nonetheless, much remains to be accomplished to reach the overall objective for these types of plants (Thakur et al., 2020). One of the fundamental challenges associated with the conservation of cryptogams is the acclimatization of species to artificial environments. In comparison to many vascular plants, cryptogams do not have roots and specialized water transport tissues, which means that they absorb nutrients and moisture directly from their surroundings (Gaskin et al., 2001).

Cryptogams cannot survive successfully when deprived of their necessary microbial partnerships in controlled environments. Reaching suitable conservation targets requires thorough biological and biochemical studies on affected species alongside modern solutions for maintaining them outside their natural environments (Deori et al., 2022).

The limited interest in funding cryptogamic conservation remains a significant problem, as these significant organisms receive less support than vascular plants (Singh et al., 2018). Conducting additional research and creating awareness initiatives alongside ensuring sufficient financial backing are vital steps to include cryptogams in sustainable conservation programs. Current global temperature elevations, along with altered precipitation patterns, pose an immediate danger to cryptogams (Szűcs, 2023). The delicate nature of cryptogams makes them vulnerable to damage caused by pollution because airborne pollutants, together with heavy metals and acid rain, harm them critically (Wasser et al., 1995).

Considering these challenges, the following research aims to develop cost-efficient conservation solutions at both local and global levels. Traditional methods like protected areas and botanical gardens do not meet cryptogram microhabitat needs. Alternative approaches like controlled environment cultivation, genomic research and cryopreservation provide promising long-term solutions. CEC, including bioreactors and artificial growth chambers, helps in developing optimal growing conditions.

PRINCIPLES OF ACCLIMATISATION AND ADAPTATION

Living organisms use acclimatization along with adaptation to survive during environmental changes. Acclimatization describes the brief physiological developments and biochemical transformations that occur in a living organism to respond to environmental change factors, including weather variables and intensity of sun exposure (Samanta et al., 2023). Cryptogams can maintain survival through this non-genetic and reversible adjustment, which helps them overcome seasonal changes and sudden environmental stresses.

Mosses and liverworts expand for liquid absorption during periods of excess water, but they reduce metabolic activity through desiccation tolerance to avoid water depletion in dry conditions (Dilrukshi et al., 2024). Throughout extended periods, evolution adapts to genetic changes that result in improved survival between many generations in targeted environments. The reproductive patterns of cryptogams have adapted through modifications that assist spore dispersal at favourable conditions, while these organisms employ thick cuticles for water preservation and pigments that provide additional UV defence (Mohan et al., 2017).

It is important to understand how much physiological adaptation can help them create strategies which enable successful cryptogam cultivation in artificial environments, so these plants can exist outside their natural habitats. The survival of cryptogams depends entirely on accessible environmental factors like temperature, along with moisture and necessary light exposure for survival (Hylander et al., 2007).

TECHNOLOGICAL AND ECOLOGICAL APPROACHES TO SPECIES CONSERVATION

The artificial production of simulated natural habitats through Controlled Environment Cultivation (CEC) exists as one main technological solution. Research environments with regulated conditions enable scientists to use LED light systems, automated misters, and climate control equipment for achieving optimal cryptogam growth (Szűcs, 2023). Cryptogams face survival challenges in the present that need combinations of technological developments with ecological preservation strategies (figure 2).

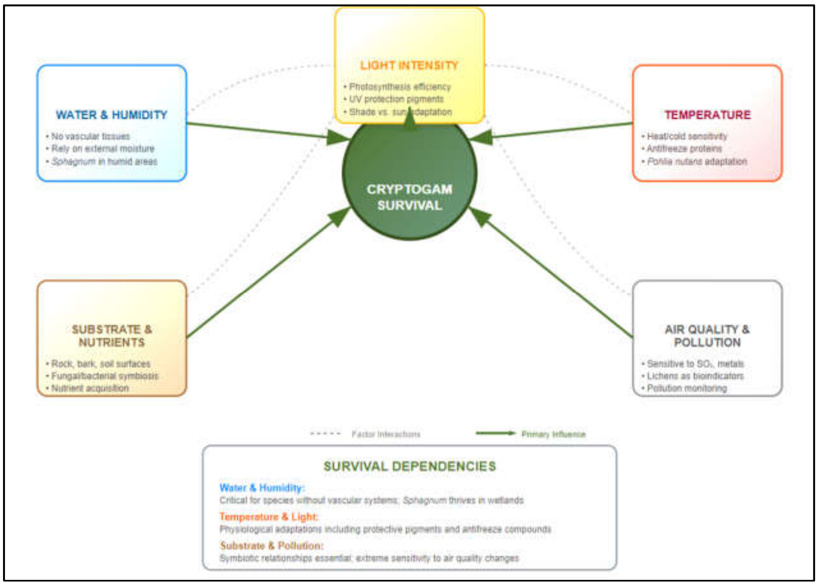

Figure 2: Environmental & Physiological Factors Influencing Cryptogam Survival

The method of cryopreservation combined with tissue culture allows researchers to store and multiply cryptogams for prolonged periods (Hicklenton et al., 1976).

The combination of genetic and bioinformatics research techniques delivers important data about cryptogam adaptive capabilities to improve their conservation outcome.

ECOLOGICAL CONSERVATION APPROACHES

Establishing protected areas and conservation zones remains essential for cryptogam conservation since they support native ecosystems, which lowers dependence on artificial cultivation (Singh et al., 2022). Local community participation in cryptogam monitoring programs, as well as propagation and reintroduction initiatives, builds community awareness to turn cryptogam conservation into a social joint effort (Chandran et al., 2011).

The evolution of these plants indicates pollution status, which makes them vital for area air quality evaluations. Environmental policies must include cryptogam monitoring as a component so that governments, through their policymakers, can enact strong pollution control measures to protect their habitats (Samanta et al., 2023). Conservation strategies that combine translocation and assisted migration of species work together with adaptive planning to help cryptogams gain footholds in stable regions where they can survive through altering environmental patterns.

Organisms within cryptogamic groups need genetic adaptation to survive when living in extreme environmental networks. The antifreeze proteins that Arctic mosses have developed serve to stop crystallization thus enabling them to withstand ice formation during freezing temperatures (Cervera et al., 2024). The desert bryophytes use thickened cuticles along with water-storage tissues to fight against long dry periods. The high-altitude ferns protect themselves from strong winds and high UV radiation by generating protective pigments and strengthening their cell walls (Varela et al., 2021). The process of genetic adaptation needs to be understood in conservation because it helps explain how species handle environmental challenges through time (Masyagina et al., 2024). The study of genetic adaptation mechanisms allows scientists to identify inclusive species which helps them predict biodiversity shifts along with developing strategies to defend cryptogams from climate change and habitat destruction shows table 1.

Table1: The Acclimatization and their corresponding adaptations of cryptogams

Aspect	Acclimatization	Genetic Adaptation
Definition	Acclimatization refers to a temporary physiological, biochemical, or morphological response that an individual organism undergoes to cope with environmental changes during its lifetime (Varela et al., 2021; Salinas et al., 2022).	Genetic adaptation is a permanent, heritable change in a population's genetic makeup that occurs over multiple generations due to natural selection (Powerset et al., 1991, Mallen-Cooper et al., 2023).
Timescale	Acclimatization occurs over a short period, typically within hours, days, or weeks, and lasts only as long as the environmental conditions require it (Varela et al., 2021).	Genetic adaptation occurs over long timescales, often taking multiple generations, thousands, or even millions of years, as advantageous traits become fixed within a population (Mayo de la Iglesia et al., 2024).

Reversibility	The changes resulting from acclimatization are reversible, meaning that once the environmental stress is removed, the organism returns to its original state (Szűcs, 2023).	Genetic adaptation is irreversible in the short term, as once a beneficial trait becomes part of the genetic code, it remains in the species unless further evolutionary changes occur (Mallen-Cooper et al., 2023).
Genetic Involvement	Acclimatization does not involve any changes to an organism's genetic code. Instead, it is based on physiological plasticity, where existing genetic traits allow for temporary modifications to cope with environmental fluctuations (Varela et al., 2021).	Genetic adaptation involves changes in the DNA sequence through mutations, genetic recombination, and the selection of beneficial traits that enhance survival and reproduction over multiple generations (Salinas et al., 2022, Bomblies et al., 2022).
Mechanism	The process of acclimatization is regulated by temporary modifications in gene expression, enzyme activity, and cellular processes that allow the organism to adjust to changing environmental conditions (Schultz et al., 2022).	Genetic adaptation is driven by natural selection, where individuals with traits that provide a survival advantage in a given environment are more likely to reproduce and pass these traits to future generations (Mallen-Cooper et al., 2023, Zhang et al., 2024).
Scope of Change	Acclimatization affects individual organisms, allowing them to survive temporary environmental variations without passing the acquired traits to their offspring (Varela et al., 2021).	Genetic adaptation affects entire populations, leading to long-term evolutionary transformations that become permanently embedded in the species' genetic makeup (Mayo de la Iglesia et al., 2024).
Environmental Triggers	Acclimatization is triggered by short-term environmental factors such as sudden temperature fluctuations, changes in humidity, variations in light intensity, or differences in nutrient availability (Zou et al., 2025).	Genetic adaptation is driven by long-term environmental pressures such as climate shifts, habitat alterations, prolonged droughts, or persistent competition for resources (Bomblies et al., 2022, Mallen-Cooper et al., 2023).
Examples in Cryptogams	Certain mosses adjust their photosynthetic rate based on light intensity, enabling them to maximize energy production under varying conditions. Lichens can produce secondary metabolites such as usnic acid to protect themselves from increased UV radiation in high-altitude environments. Some ferns enter a dormant state during periods of drought and reactivate once moisture becomes available (Varela et al., 2021, Salinas et al., 2022).	Arctic mosses have developed antifreeze proteins over generations to prevent ice formation in their cells and tolerate freezing temperatures. Desert bryophytes have evolved thicker cuticles that reduce water loss and enhance survival in arid environments. High-altitude ferns have developed structural modifications that help them resist strong winds and intense UV radiation (Mayo de la Iglesia et al. 2024, Mallen-Cooper et al., 2023).

Role in Survival	Acclimatization provides an immediate survival advantage by allowing organisms to adjust to temporary environmental challenges, ensuring their short-term well-being (Schultz et al., 2022).	Genetic adaptation ensures the long-term survival of a species by promoting traits that enhance fitness and reproductive success in specific environments, allowing the species to persist over generations (Mallen-Cooper et al., 2023).
Significance in Conservation	Understanding acclimatization is essential for researchers working on conservation efforts, as it helps determine how cryptogams can be cultivated in artificial environments by replicating natural acclimatization conditions (Varela et al., 2021, Bühler et al., 2024).	Genetic adaptation provides insights into how cryptogams may evolve in response to long-term climate changes, helping conservationists develop strategies for preserving species that are at risk due to environmental shifts (Gufwan et al., 2025, Cervera et al., 2024).

Cryptogams demonstrate different stress response mechanisms based on how fast or prolonged environmental conditions become unfavorable (Varela et al., 2021, Salinas et al., 2022). Individuals can survive through short-term responses which trigger internal physiological transformations along with biochemical processes inside their lifetime (Schultz et al., 2022). Mosses and other plants respond quickly to environmental stress through water absorption, make photosynthesis adjustments, and produce protective pigments (Varela et al., 2021). When in a desiccation-tolerant state mosses reduce their metabolism to survive dry conditions before their growth resumes after receiving moisture (Salinas et al., 2022). The high-altitude environment prompts lichens to adjust their secondary metabolite output for increased UV radiation protection (Mayo de la Iglesia et al., 2024).

Genetic adaptations which form through time represent the mechanisms for long-term responses across populations (Powerset et al., 1991, Mallen-Cooper et al., 2023). Natural selection makes these permanent alterations in population genetics (Zhang et al., 2024). The adaptation of Arctic mosses includes the natural development of antifreeze proteins which protects them against ice crystals in extremely cold conditions (Mayo de la Iglesia et al., 2024). Proof of cryptogamic adaptation comes through their successful implementation of both fast acclimatization and evolutionary changes for extreme conditions survival (Varela et al., 2021, Cervera et al., 2024).

DISCUSSION

The Ponds field ecosystem provides an environmental favorable for the growth of Cyanobacteria with respect to them requirements for light, water, high temp and nutrient availability (Roger et al., 1993). Cyanobacteria are found all over the world in environmentally as diverse as Antarctic soil and volcanic hot spring often where no other vegetation can exist. (Knoll, 2008). Some Cyanobacterial strains i.e., *Aulosira fertilissima*, *Anabaena variabilis*, *Nostoc muscorum*, and *Tolpothrix tenuis* are being used in algal bio fertilizer technology (Kaushik, 2014). Most of the nitrogen of Cyanobacteria is released only after decomposition and autolysis (Martinenz, 1984). The majority of Cyanobacterial strains release an insignificant amount of ammonia during their growth period (Martinenz, 1984). Search for continuous ammonia secreting Cyanobacteria strains are one of the primary goals of plant biologist. The Cyanobacteria strain was isolated, characterized, and studied for ammonia secreting properties. Cyanobacteria are very resistant to extreme environmental condition and even they tolerate to high temperature up to 50ºC. They are increasing importance in frontier areas of biotechnology.

CONCLUSION

This review paper addresses these gaps by investigating the physiological and biochemical responses of cryptogams to artificial conditions and understanding their acclimatization mechanisms in controlled environments. This study will contribute to more effective conservation strategies that include both cryptogams and their microorganisms. It will also propose standardized artificial cultivation methods for specific cryptogam groups, and improve propagation success and scalability. Educational settings that include research centres must include cryptogam studies in their environmental programs to teach upcoming generations about these organisms' ecological roles so they can participate in conservation programs. The results will also inform policy recommendations to integrate cryptogams into global biodiversity conservation frameworks. By filling these gaps, this review work will contribute to the field of cryptogam conservation science, and ensure the long-term survival of these organisms in natural and artificial environments.

REFERENCES

Baniya, C.B. (2010). Vascular and cryptogam richness in the world's highest alpine zone, Tibet. *Mountain Research and Development*, 30(3), 275–281.

Bao, T., Jia, G., & Xu, X. (2023). Weakening greenhouse gas sink of pristine wetlands under warming. *Nature Climate Change*, 13(5), 462-469.

Bezbarua, P., Bezbarua, A., & Baruah, C. K. (2024). Status of Grassland and Its Management Scenarios in the Himalayan Global Biodiversity Hotspot with Special Reference to Manas Biosphere Reserve. In *Biodiversity Hotspot of the Himalaya* (pp. 355-419). Apple Academic Press.

Bomblies, K., & Peichel, C. L. (2022). Genetics of adaptation. *Proceedings of the National Academy of Sciences*, *119*(30), e2122152119.

Bühler, M., Hollenbach, P., Köhler, L., & Armstrong, R. (2024). Unlocking resilience and sustainability with earth-based materials: a principled framework for urban transformation. *Frontiers in Built Environment*, *10*, 1385116.

Cervera, R., Villalba, M. R., & Sánchez, J. (2024). The Artificial Tree: Integrating Microalgae into Sustainable Architecture for CO2 Capture and Urban Efficiency—A Comprehensive Analysis. *Buildings*, *14*(12), 4045.

Chapman, P. M. (2008). Environmental risks of inorganic metals and metalloids: a continuing, evolving scientific odyssey. *Human and Ecological Risk Assessment*, *14*(1), 5-40.

Cornelissen, J. H., Lang, S. I., Soudzilovskaia, N. A., & During, H. J. (2007). Comparative cryptogam ecology: a review of bryophyte and lichen traits that drive biogeochemistry. *Annals of botany*, *99*(5), 987-1001.

Das, P., Joshi, S., Rout, J., & Upreti, D. K. (2012). Exploration of homegardens as important lichen conservation areas in Dargakona Village of Southern Assam, Northeast India. *Journal of Functional and Environmental Botany*, *2*(2), 87-95.

Deori, C., & Talukdar, S.R. (2022). Checklist of the dicotyledons and vascular cryptogamic flora of Barnadi Wildlife Sanctuary, Assam, India. *Pleione*, *16*(2): 130 – 145.

Dey, D. (2021). Study of plant diversity in and around central university of Himachal Pradesh TAB campus, Shahpur and its medicinal uses. *Journal of Scientific Research*, *65*(1), 88-104.

Dilrukshi, H. A. C., Ruklani, N. C. S., & Rubasinghe, S. C. K. (2024). Cryptogams as bio-indicators for ecosystem monitoring in Sri Lanka: a comprehensive review and recommendations. *Environmental Monitoring and Assessment*, *196*(12), 1231.

Dudani, S. N., & Mahesh, M. K. (2017). Conservation strategies for the hygrophilous Pteridophytes of Central Western Ghats. In *Ntl. Conf. on Conserv. and Mgmt of Wetland Ecosystems-LAKE 2012* (pp. 6-8).

Dudani, S.N., Chandran, M.S., & Ramachandra, T.V. (2011). Conservation of pteridophytes to maintain a vital link between the lower and higher groups of plants. *Sahyad e-news,* 33, 2–34.

Gall, C., Nebel, M., Quandt, D., Scholten, T., & Seitz, S. (2022). Pioneer biocrust communities prevent soil erosion in temperate forests after disturbances. *Biogeosciences*, *19*(13), 3225-3245.

Gaskin, S., & Gardner, R. (2001). The role of cryptogams in runoff and erosion control on Bariland in the Nepal middle hills of the Southern Himalaya. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *26*(12), 1303-1315.

Gianoli, E., & Molina-Montenegro, M. A. (2021). Evolution of physiological performance in invasive plants under climate change. *Evolution*, *75*(12), 3181-3190.

Gufwan, L. A., Peng, L., Gufwan, N. M., Lan, S., & Wu, L. (2025). Enhancing soil health through biocrusts: A microbial ecosystem approach for degradation control and restoration. *Microbial Ecology*, *88*(1), 1-26.

Hicklenton, P. R., & Oechel, W. C. (1976). Physiological aspects of the ecology of Dicranum fuscescens in the subarctic. I. Acclimation and acclimation potential of CO2 exchange in relation to habitat, light, and temperature. *Canadian Journal of Botany*, *54*(10), 1104-1119.

Hylander, K., & Jonsson, B. G. (2007). The conservation ecology of cryptogams. *Biological Conservation*, *135*(3), 311-314.

Jairus, K., Lohmus, A., & Lohmus, P. (2009). Lichen acclimatization on retention trees: a conservation physiology lesson. *Journal of applied ecology*, *46*(4), 930-936.

Jung, P., Briegel-Williams, L., Werner, L., Jost, E., Schultz, M., Nürnberg, D.J., Grube, M., & Lakatos, M. (2024). A direct PCR approach with low-biomass insert opens new horizons for molecular sciences on cryptogam communities. *Applied and Environmental Microbiology,* 90(3): e00024-24.

Kluge, M., & Brulfert, J. (2000). Ecophysiology of vascular plants on inselbergs. In *Inselbergs: biotic diversity of isolated rock outcrops in tropical and temperate regions* (pp. 143-174). Berlin, Heidelberg: Springer Berlin Heidelberg.

Li, X. R., Chen, Y. W., & Yang, L. W. (2004). Cryptogam diversity and formation of soil crusts in temperate desert. *Annals of Arid Zone*, *43*(3/4), 335.

Lockhart, K., Sandino, J., Amarasingam, N., Hann, R., Bollard, B., & Gonzalez, F. (2025). Unmanned aerial vehicles for real-time vegetation monitoring in Antarctica: A review. *Remote Sensing*, *17*(2), 304.

Mao, G. (2021, July). A Study of Bio-Computational Design in Terms of Enhancing Water Absorption by Method of Bionics Within the Architectural Fields. In *The International Conference on Computational Design and Robotic Fabrication* (pp. 102-113). Singapore: Springer Singapore.

Martínez-Abaigar, J., & Núñez-Olivera, E. (2022). Bryophyte ultraviolet-omics: from genes to the environment. *Journal of Experimental Botany*, *73*(13), 4412-4426.

Masyagina, O. V., Evgrafova, S. Y., Kovaleva, N. M., Detsura, A. E., Porfirieva, E. V., Menyailo, O. V., & Matvienko, A. I. (2024). The Hydration-Dependent Dynamics of Greenhouse Gas Fluxes of Epiphytic Lichens in the Permafrost-Affected Region. *Forests (19994907)*, *15*(11).

Mayo de la Iglesia, R., Miserere, L., Vust, M., Theurillat, J. P., Randin, C., & Vittoz, P. (2024). Divergent responses of alpine bryophytes and lichens to climate change in the Swiss Alps. *Journal of Vegetation Science*, *35*(4), e13292.

Mishra, G. K., Mohan, J., & Mohan, N. Recent Status of Cryptogam in India.

Nygaard, R. T. (1975). Acclimatization effect in photosynthesis and respiration. In *Fennoscandian Tundra Ecosystems: Part 1 Plants and Microorganisms* (pp. 163-167). Berlin, Heidelberg: Springer Berlin Heidelberg.

Oishi, Y. (2024). Cryptogam biomass estimation using taxonomic and life form models for accurate assessment. *Scientific Reports*, *14*(1), 19038.

Pane, C., Nicastro, N., Manganiello, G., Carotenuto, F., Pallottino, F., & Costa, C. (2023, November). Hyperspectral imaging to oversee the status of baby leaf vegetable crops: The Agrofiliere Project results. In *2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* (pp. 501-505). IEEE.

Powers, D. A., Lauerman, T., Crawford, D., & DiMichele, L. (1991). Genetic mechanisms for adapting to a changing environment. *Annual Review of Genetics*, *25*(1), 629-660.

Salinas, P., Mazon, M., Carrion-Paladines, V., Cumbicus, N., Guzman, P., Giordani, P., & Benitez, A. (2022). Influence of soil and elevation on roadside cryptogam diversity in the tropical Andes. *Forest Ecosystems*, *9*, 100061.

Samanta, S., Panchadhyaee, P., Maity, T. R., Nanda, K., & Samanta, A. (2023). Development of a growth chamber for cryptogams: a step toward ex situ conservation. *Brazilian Journal of Botany*, *46*(3), 661-666.

Saraphol, S., Rindi, F., & Sanevas, N. (2024). Diversity of epiphytic subaerial algal communities in Bangkok, Thailand, and their potential bioindicator with air pollution. *Diversity*, *16*(1), 55.

Schultz, N. L., Sluiter, I. R., Allen, G. G., Machado-de-Lima, N. M., & Muñoz-Rojas, M. (2022). Biocrust amendments to topsoils facilitate biocrust restoration in a post-mining arid environment. *Frontiers in Microbiology*, *13*, 882673.

Singh, J., Singh, R. P., & Khare, R. (2022). Higher rate of pigment synthesis in Antarctic plants: a strategy of survival under UV radiations. In *Assessing the Antarctic Environment from a Climate Change Perspective: An Integrated Approach* (pp. 255-275). Cham: Springer International Publishing.

Singh, K. P., Singh, P., & Sinha, G. P. (2018). Lichen diversity in the Eastern Himalaya biodiversity hotspot region, India. *Cryptogam Biodiversity and Assessment*, *18*, 71-114.

Strother, P. K. (2000). Cryptospores: the origin and early evolution of the terrestrial flora. *The Paleontological Society Papers*, *6*, 3-20.

Subbaiyan, R., Ganesan, A., & Dhanuskodi, S. (2023). Ecolichenology of Eastern Ghats diversity against climatic fluctuations in Kolli Hills, India. *Biodiversitas Journal of Biological Diversity*, *24*(1), 625-635.

Thakur, P., & Chander, H. (2020). Floristic studies on cryptogams of Sujanpur-Tihra region of Himachal Pradesh. *Asian Journal of Advanced Basic Sciences*, *8*(2), 17–20.

Varela, Z., Real, C., Branquinho, C., Do Paço, T. A., & Cruz de Carvalho, R. (2021). Optimising artificial moss growth for environmental studies in the Mediterranean area. *Plants*, *10*(11), 2523.

Wang, Q. H., Zhang, J., Liu, Y., Jia, Y., Jiao, Y. N., Xu, B., & Chen, Z. D. (2022). Diversity, phylogeny, and adaptation of bryophytes: insights from genomic and transcriptomic data. *Journal of Experimental Botany*, *73*(13), 4306-4322.

Wasser, S. P., Nevo, E., Vinogradova, O. N., Navrotskaya, I. L., Ellanskaya, I. A., Volz, P. A., ... & Kondratyuk, S. Y. (1995). Diversity of cryptogamic plants and fungi in "Evolution Canyon", Nahal Oren, Mount Carmel Natural Preserve, Israel. *Israel Journal of Plant Sciences*, *43*(4), 367-383.

Zhang, Y., & Liu, B. (2024). Biological soil crusts and their potential applications in the sand land over Qinghai-Tibet Plateau. *Research in Cold and Arid Regions*, *16*(1), 20-29.

Zhang, Z., Ai, S., Teng, W., Meng, X., Li, R., Yang, F., & Cheng, K. (2024). Artificial carbon materials' impact on soil fertility and greenhouse gas emission. *Journal of Soils and Sediments*, *24*(4), 1623-1638.

Zou, J., Liu, W., Wang, D., Luo, S., Yang, S., Ding, X., & Shi, M. (2025). Comparative study of artificial light plant factories and greenhouse seedlings of SAOPOLO tomato. *Plos one*, *20*(3), e0314808.

****