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Physiological activity and characterization of bryophytes: A Review

Ransing M.S., Chavan S. J. and Mali. B.S

Department of Botany, Tuljaram Chaturchand College of Arts, Science and Commerce, India

ABSTRACT

Bryophytes show a diverse range of physiological processes that define their ecological adaptability and functional significance. Early physiological investigations have highlighted key activities such as photosynthesis, chlorophyll synthesis, and the metabolism of proteins and carbohydrates, which are important for their survival under fluctuating environmental conditions. Enzymatic markers, like protease and nitrate reductase, serve as important indicators of metabolic adjustments during stress. The accumulation of reactive oxygen species (ROS) in bryophytes under adverse conditions further highlights the importance of these enzymes, with nitrate reductase playing a central role in nitrogen assimilation and overall metabolic regulation.

Beyond physiological responses, recent studies have expanded the characterization of bryophytes through their capacity to mediate the synthesis of silver nitrate nanoparticles. These biologically derived nanoparticles consist of antimicrobial, anti-inflammatory, antioxidant, and other pharmacological properties. Under this research, Liquid Chromatography–Mass Spectrometry (LC-MS) have become important for profiling bryophyte chemistry. LC-MS enables the detection of different secondary metabolites, including phenols, terpenoids, flavonoids, and alkaloids hence helping in a deeper understanding of their bioactive potential and ecological roles.

Future research should aim to integrate advanced biochemical, molecular, and imaging approaches to elucidate unexplored metabolic pathways and stress-response mechanisms in bryophytes. Such efforts will not only extend the knowledge of their biology but also support the development of bryophyte-derived compounds and nanoparticles for sustainable agricultural practices, environmental management, and therapeutic innovation.

KEY WORDS

Bryophytes; Bioactive compounds; Silver nanoparticles; LC-MS

ARTICLE HISTORY

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Introduction

Bryophytes are important in land plant it consist of mosses, liverwort and hornworts, and they are second largest plant group in ecosystems. Bryophyte is a group of photosynthetic organisms which were among the first colonize the terrestrial environment. They are similar to the vascular plants. In general, large area occupy in bryophytes are biological active compounds such as proteins, organic acids, terpenoids substance obtained from various species. Bryophytes are divided into three types [1].

Mosses (Musci), Hornworts (Anthocerotae), Liverworts (Hepaticae). It is used to biological active agricultural area, and pharmaceutically important bryophytes can be found every type of habitat except oceans. Bryophytes represent in a valuable source of bioactive compound they are secondary metabolites and proteins. Bryophytes are the nonvascular, nonflowering land plant group under the classes' liverwort. Hornwort, mosses, and bryophytes can survive on rocks and bare soil [2]. Bryophytes are an important group of land plants after flowering plants, with 24,000 species found globally. Bryophytes hold a specific transitional position in the evolution cycle of cryptogams, reflecting key adaptations between aquatic flora and terrestrial plant lineages. Bryophytes are terrestrial plants that form dense cushion-like colonies across diverse substrates. They have survived across diverse habitats as they rarely face competition from higher plants. For such small organisms, the ground-level microclimate often differentiates from conditions measured by standard meteorological methods , with temperature and humidity fluctuations (Vitt and Darigo). They contain chlorophyll a and b, xanthophylls, and carotenes, and they store starch within their plastids [3].

Bryophytes contain flavonoids, a group of pigments capable of UV light absorption. In mosses and liverworts within the plant kingdom, all vegetative structures, including the leaves, stem, and rhizoids, contain only one set of chromosomes that determines their morphology and function. The bryophyte sporophyte is unbranched, and secondary metabolites, such as flavonoids, terpenes, and fatty acid derivatives, form a chemical barrier against potential pathogens, which is used in various traditional medicines, particularly for treating infections and wound cleaning [4]. Further research on bryophytes has further confirmed their antimicrobial properties.

Carbohydrates form the major biochemical components of bryophytes, compared to lignin, which is generally low. It has been suggested that certain carbohydrates significantly contribute to the biological stability of bryophytes and their amino acids binding capacity within protein structures, thereby causing their deactivation (Bland et al. 1968). However, some studies challenge the role of carbohydrate-bound carboxylic groups, including ironic acid residues, as major structural units. Preliminary biochemical investigations on western Himalayan liverworts were conducted in India [5]. Quantitative analyses of carbohydrate, protein, chlorophyll content, and the enzymatic activities of α-amylase, β-amylase, protease, and polyphenol oxidase have also been performed.

***Correspondence:** Miss. Ransing M.S, Department of Botany, Tuljaram Chaturchand College of Arts Science and Commerce, India, email: ransingmahadevi565@gmail.com

Research using advanced analytical methods such as gas chromatography and Fourier transform infrared spectrometry (FT-IR) for structural characterization remains limited. The objective of this review is to analyze and compare the chemical composition of several common bryophytes in Latvia using elemental, spectral, and destructive analytical techniques [6].

Global Status

Physiological characteristics and photosynthetic responses

Physiologically, bryophytes function similarly to normal C3 plants. But, due to their small size and specific environmental physiology, their photosynthesis rate reduces rapidly in correlation with water loss. This situation is important in moist habitats, where maximum photosynthesis is observed, but rates reduce under high-water stress conditions. To study these physiological changes, infrared gas analysis is frequently used for the photosynthesis measurement [7]. Further studies have recorded photosynthetic light responses and determined the proportions of Chlorophyll a, Chlorophyll b, and the total carotenoids.

Nutrient assimilation and chemical composition

Bryophytes show complex nutrient interactions. Research has expressed the effect of nitrogen oxide on nitrate assimilation in bryophytes. Enzymatic studies have also analyzed nitrate reductase activity in two specific species: Brachythecium rutabulum (Hedw) Schimp and Atrichum undulatum (Hedw) P. Beauv. Reports have identified the presence of major nutrients such as N, P, K, Ca, Mg, Na, and Fe [8].

Advances in analytical chemistry have allowed for the detailed chemical characterization of common bryophytes, such as those found in Latvia. Techniques such as chemical analysis via FT-IR (Fourier Transform Infrared Spectroscopy) and GC-MS (Gas Chromatography-Mass Spectrometry) can be used for the moss chemical taxonomy. These methods are essential for the study and determination of secondary metabolites and structural composition.

Secondary metabolites and bioactivity

There is a significant shift in using bryophytes as a source of secondary metabolites. These compounds are recorded for being antibacterial and antitoxic. Also, secondary metabolites play an important role in stress tolerance, stress senescence, and specialized metabolic pathways in bryophytes [9].

Research has also studied the chemical diversity and classification of secondary metabolites across nine different species. Seasonal variations significantly impact these species [10]. A study of nine different bryophytes using LC-MS revealed their relationships among species, seasons, ecological characteristics, and hierarchical clustering.

Antioxidant properties and lipidomics

Bryophytes are recognized as a potential source of antioxidants. Oxidative stress, which is a primary reason for the imbalance between antioxidants (such as protease and reductase) and damaged proteins, is a cause of various diseases caused by free radicals. Similarly, studies have examined the seasonal variation of antioxidant-enzymatic responses in desiccation-tolerant bryophytes, such as Syntrichia ruralis (Hedw) F. Weber & D. Mohr [11]. Also, antimicrobial alpha-amylase inhibitory activity has been recorded.

In lipidomic, mass spectroscopy and LC-MS have been utilized to screen the lipidomes of Icelandic bryophytes, revealing a high content of polyunsaturated fatty acids.

Ecological adaptations and developmental studies

Bryophytes present unique mechanisms for environmental adaptation. Lithophytic bryophytes possess specific mechanisms for adapting to Karst environments, which are characterized by high calcium levels.

In vitro culture and microscopic observation have been conducted on Dolichomitriopsis diversiform is. These reports trace the cycle from spore germination to the young gametophyte formation [12]. Finally, hypotheses regarding Sphagnum spores suggest a positive response to single and combined treatments of dead material and smoke, demonstrated by increased germination, whereas spore germination decreased under high temperatures.

Indian Status

Chloroplasts, pigments, and stress protection

Studies on the chloroplasts reveal that chlorophyll and carotenoid pigments are intimately associated with each other. Based on these studies of pigment dynamics, Kupier highlighted the role of tocopherol antioxidants in aiding the photooxidation process and protecting chlorophyll from degradation [13].

Beyond oxidative stress, environmental toxicity is a major study area. Some heavy metals have toxic effects on bryophytes. Esposito S et al. studied the presence of heavy metals in moss samples. Moreover, polysaccharides play a major role in chemical diversity, stress tolerance, and other physiological functions [14].

Biochemical interactions and seed germination

Bryophytes consist of significant structural functions and have affected the germination of different seed varieties, particularly in species within the family Marantaceae [15]. The mechanism has been studied through enzyme activities, through changes in α-amylase and β-amylase which decrease the primary growth related to carbohydrate assimilation and protease activity associated with protein metabolism.

In recent studies, mosses were collected from different sites in the Western Ghats of Maharashtra. These samples were used for the estimation of proteins and carbohydrates. Furthermore, it was observed that water extracts of these mosses influenced the seed germination growth of various plants [16].

Morphological adaptations and mineral analysis

Detailed mineralogical studies analyzed the nutrients in mosses from Maharashtra, specifically Barbula unguiculata, Hypnum reflexum, and Stereophyllum anceps.

In extreme environments, such as Ganga Nagar district in Rajasthan, studies focused on morphological and anatomical adaptations [17]. These include xeric condition traits such as tufts of tough rhizoids and longer rhizoids.

Phytochemistry, Nanotechnology, and In-Vitro Culture

Biotechnology advancements have led to the study of synthesized silver nanoparticles and their characterization from Campylopus flexuosus (Hedw). Similarly, preliminary phytochemical analysis and characterization have been conducted on Bryum coronatum Schwager.

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Conservation efforts for threatened species have also used these techniques. Through GC-MS analysis, researchers identified flavonoids, alkaloids, saponins, steroids, and terpenoids in the threatened Indian liverwort Cryptomitrium himalayense Kashyap. This rare species was transmitted successfully using an in-vitro culture method [18]. Subsequent development of the thallus was reported during acclimatization and transfer into soil, where the plants were reported to produce gametangia.

Finally, some researchers have studied the in-vitro biological activity of plants. In this context, the phytochemical analysis of the liverwort Targionia loberiana was conducted.

Maharashtra Status

Biochemical composition and pigment analysis

Fundamental biochemical profiling has been important to recent bryological research. During the study on the contents of specific Bryophytes (II Musci), parameters such as the chlorophyll content, protein, carbohydrates, and RNA have been studied across various taxa of mosses.

Specific attention has been given to photosynthetic pigments with chlorophyll and carotenoid concentrations measured in five bryophytes collected from the Panhala region of the Kolhapur district. Studies on pigment chlorophyll isolation and the estimation of different bryophytes for their biochemical properties were conducted [19]. This study analyzed the amount of chlorophyll concentration content in six species belonging to the classes Anthocerotae, Hepaticae, and Musci from different localities of Purandar Fort, Maharashtra.

Heavy metal accumulation and environmental monitoring

Bryophytes are excellent bioindicators of environmental health. A study on the metal absorption by two bryophytes was conducted in the Koyna Wildlife Sanctuary, India. In this study, the estimation of important heavy metals like Cu, Zn, Pb, Ni, Cd, and Cr have been carried out on two bryophyte species using atomic absorption spectroscopy.

Nanotechnology and Green Synthesis

Research has demonstrated plant-mediated synthesis of silver nanoparticles using the bryophyte Fissidens minutus and evaluated its anti-microbial activity. The present study highlights the use of primitive plant forms for silver nanoparticle synthesis [20]. Similarly, moss (Bryophyte) directed synthesis and characterization of silver nanoparticles from Campylopus flexuous has been successfully documented.

Floristics, diversity, and conservation

Western Ghats remain a major region for floristic studies. Researchers have conducted studies on coticules mosses from Panhalagad in the Western Ghats of Maharashtra, India. This effort contributed to a checklist from the Western Ghats of Maharashtra, India, with Maharashtra being the largest land area in southern India without a comprehensive checklist of mosses [21]. Research also explored secondary metabolites and enzyme activity on some moss species from the Western Ghats.

Current research focuses on the study of moss diversity and secondary metabolites analysis using FTIR, with efforts to preserve them via ex situ conservation methods in Baramati Tahshil, Pune, and Revdanda Raigad, Maharashtra, India [22]. Also, biological interactions have been studied through the analysis and fungal isolation of some mosses, specifically Riccia discolor and Targionia hypophylla, from the Baramati district, Pune, Maharashtra, India.

Conclusion

This work clarifies the physiological approach towards bryophytes and characterization of bryophytes. In physiological studies on bryophyte-like chlorophyll, protein, carbohydrates, and secondary metabolites, some enzymes. Characterization like LCMS, also includes silver nanoparticles. This method is also useful for biochemical analysis of compounds. Silver nano particles is the highly fascinating science among researchers. Nanotechnology is embracing many fields like engineering, electronics, cosmetic industries, agriculture and in life science, especially the biomedical field, to manufacture the devices and drug delivery. This biological method Physiological studies, are detected from bryophytes remarkable more leafy members than thalloid members and mosses. The work done from last six - seven decades includes more than a hundred research papers available in literature.

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