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From Neglected Lineages to Emerging Bioresources: The Thirst for Research in Primitive Botany and Its Applications in the Era of Biodiversity, Biotechnology and Sustainable Development

D. Herin Sheeba Gracelin [1*], P. Benjamin Jeya Rathna Kumar[2]

[1*]Assistant Professor, Department of Botany,
Sarah Tucker College (Autonomous), Tirunelveli - 627 007,
Affiliated to Manonmaniam Sundaranar University, Tirunelveli, Tamil Nadu, India.
*E-Mail: herinstc@gmail.com, https://orcid.org/0000-0003-1370-5889
Tel: 0091- 462- 2530597, Fax: 0091- 462-2531023.
[2]Assistant Professor, Department of Botany, Kamaraj College (Autonomous), Thoothukudi - 628003,
Affiliated to Manonmaniam Sundaranar University, Tirunelveli, Tamil Nadu, India.
E-Mail: benjaminkcollege@gmail.com
Tel: 0091- 461- 2970107.

ABSTRACT
Algae, bryophytes, pteridophytes and their associated microbial communities represent evolutionarily informative systems that preserve distinctive biological strategies for survival, reproduction, stress tolerance and environmental adaptation. Their apparent simplicity conceals an extraordinary diversity of biochemical compounds, genetic resources and ecological functions with considerable potential for pharmaceutical, agricultural, environmental, industrial and biotechnological applications. Research on primitive botanical subjects remains constrained by taxonomic neglect, insufficient field exploration, limited genomic resources, inadequate culture collections, fragmented databases, shortage of specialized expertise and weak translation of basic discoveries into commercial applications. This review examines the research potential of primitive botanical groups from an interdisciplinary perspective, emphasizing taxonomy, evolutionary biology, molecular research, phytochemistry, pharmacology, agriculture, environmental biotechnology, climate resilience, conservation and bioeconomy. The review proposes that the future of primitive botany lies not merely in documenting species diversity but in transforming unexplored biological diversity into scientifically validated, ethically sourced and sustainable bioresources. Strengthening research in these neglected groups could generate novel solutions for human health, environmental restoration, sustainable agriculture and climate adaptation while simultaneously contributing to the conservation of evolutionary heritage.

Keywords: Algae, Bryophytes, Pteridophytes, Biotechnology and Ethnobotany

1. Introduction

Plant science has traditionally been organized around major botanical groups, with flowering plants receiving disproportionate attention because of their direct importance to agriculture, forestry, horticulture, medicine and industry. In contrast, algae, bryophytes and pteridophytes have frequently been described collectively as “lower” or “primitive” plants in traditional botanical literature. Modern evolutionary biology, however, has demonstrated that such terminology can be misleading because these organisms are not inferior forms of plant life but represent diverse evolutionary lineages with distinctive adaptations and highly specialized biological functions (Goffinet and Shaw, 2009; Ranker and Sundue, 2015). Consequently, the term primitive botany in this review is used in a historical and educational sense to encompass major non-flowering and early-diverging plant lineages rather than implying evolutionary inferiority. Bryophytes, for example, contribute to nutrient cycling, soil formation, water regulation, ecological succession and environmental monitoring, while also producing bioactive metabolites with antimicrobial, antioxidant, cytotoxic and anti-inflammatory properties (Glime, 2007; Asakawa et al., 2013; Chetia et al., 2025). Pteridophytes provide valuable systems for studying vascular evolution, plant development, stress physiology, phytoremediation and bioactive compound discovery (Ranker and Sundue, 2015; Sessa, 2018). Algae and cyanobacteria constitute major reservoirs of pigments, polysaccharides, lipids, proteins and specialized metabolites relevant to food, nutraceuticals, pharmaceuticals, biofuels and bioremediation (Pulz and Gross, 2004; Borowitzka, 2013; Wells et al., 2017).

The scientific importance of these organisms is closely linked to their position in the evolutionary history of life on Earth. Early photosynthetic organisms contributed to the transformation of planetary environments, while the emergence of land plants initiated major ecological changes that ultimately shaped terrestrial ecosystems (Kenrick and Crane, 1997; Delwiche and Cooper, 2015). Bryophytes provide important insights into the early adaptation of plants to terrestrial environments, whereas pteridophytes illustrate critical stages in the evolution of vascular tissues, leaves and complex sporophyte organization (Goffinet and Shaw, 2009; Ranker and Sundue, 2015). Algae, particularly green algal lineages, provide valuable evolutionary models for understanding the transition from aquatic to terrestrial plant life (Delwiche and Cooper, 2015).

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The contemporary relevance of these groups extends far beyond evolutionary interpretation. Bryophytes influence water retention, nutrient cycling, carbon storage and ecosystem development; pteridophytes participate in ecological succession and provide resources for traditional medicine and phytochemical research; and algae contribute substantially to aquatic productivity and represent promising resources for food, bioenergy, pharmaceuticals and biomaterials (Glime, 2007; Pulz and Gross, 2004; Borowitzka, 2013). Bryophytes have also attracted renewed interest because of their potential as sources of secondary metabolites and as ecological indicators, while ethnobotanical knowledge suggests that many species remain chemically and pharmacologically underexplored (Asakawa et al., 2013; Singh et al., 2016; Chetia et al., 2025).

The phrase "thirst of research" therefore reflects a major scientific gap: the biological diversity of these groups is considerably greater than the depth of research devoted to them. Many species remain poorly documented, taxonomically uncertain or chemically unexplored. This research deficit is particularly significant in biodiversity-rich regions such as the Western Ghats, Eastern Himalayas, Northeast India and tropical island ecosystems, where geographical complexity and microclimatic variation support considerable cryptogamic diversity (Ranker and Sundue, 2015).

The integration of classical taxonomy with molecular systematics, DNA barcoding, metabolomics, proteomics, transcriptomics, artificial intelligence and advanced imaging now provides an unprecedented opportunity to transform primitive botany into a modern interdisciplinary research field. This review discusses these opportunities and proposes an application-oriented research framework for discovering, characterizing, conserving and sustainably utilizing these neglected biological resources.

2. Reconsidering the Concept of "Primitive" Botany

Traditional botanical classifications often arranged algae, bryophytes and pteridophytes along a linear evolutionary sequence leading toward seed plants. Modern phylogenetic studies have replaced this simplistic ladder-like interpretation with branching evolutionary relationships. The three major bryophyte lineages—liverworts, mosses and hornworts—represent distinct evolutionary groups, while vascular plants form another major lineage with extensive internal diversification (Goffinet and Shaw, 2009; Puttick et al., 2018).

The concept of primitiveness should therefore be replaced by the idea of evolutionary distinctiveness and biological innovation. Organisms that appear morphologically simple may possess sophisticated biochemical pathways that enable them to survive desiccation, ultraviolet radiation, freezing, nutrient limitation and other environmental stresses. Such adaptations are especially valuable in an era characterized by climate instability and ecosystem degradation (Oliver et al., 2020).

Bryophytes provide an excellent example. Their capacity for desiccation tolerance and rapid recovery after rehydration represents a potentially valuable model for studying cellular protection mechanisms (Oliver et al., 2020). Similarly, pteridophytes have evolved physiological mechanisms that allow survival in diverse habitats, including nutrient-poor soils, exposed rock surfaces, wetlands and forest ecosystems. Algae exhibit remarkable metabolic plasticity, allowing them to survive salinity changes, light stress, temperature fluctuations and nutrient limitations (Borowitzka, 2013).

Therefore, the scientific question should no longer be "What can primitive plants offer?" but rather "What biological solutions have these ancient lineages evolved that remain undiscovered?"

3. Taxonomic Exploration and the Unfinished Inventory of Plant Diversity

Taxonomy forms the foundation of all biological research. Without accurate species identification, ecological studies, conservation programmes, phytochemical investigations and biotechnological development may be compromised. Yet algae, bryophytes and pteridophytes remain comparatively under-collected and under-documented in many regions.

Classical identification based on morphology remains indispensable, particularly for field-level biodiversity surveys and herbarium development. However, morphological convergence, phenotypic plasticity and cryptic species complexes can make identification difficult. Molecular approaches such as DNA barcoding and phylogenetic analysis have therefore become increasingly important for resolving taxonomic uncertainties (Parks et al., 2012).

In bryophytes, molecular markers can complement traditional morphological characters and improve species delimitation. In pteridophytes, plastid and nuclear genomic data have significantly improved understanding of relationships among lineages (Ranker and Sundue, 2015). Algal taxonomy is similarly benefiting from molecular tools because morphological variation can be strongly influenced by environmental conditions. The development of integrated taxonomy, combining morphology, anatomy, cytology, ecology, chemistry and molecular data, should become a priority. Such approaches can identify cryptic diversity and reveal geographically restricted species that may otherwise remain overlooked.

Research priorities

1.Intensive field surveys in poorly explored ecosystems.
2.Digitization of herbarium collections.
3.DNA barcoding of unidentified specimens.

4.Development of regional molecular reference libraries.
5.GIS-based mapping of species distributions.
6.AI-assisted image recognition for field identification.
7.Long-term monitoring of population trends.

The future taxonomist is therefore likely to function at the interface of field botany, molecular biology, informatics and conservation science.

4. Bryophytes: From Ecological Indicators to Biotechnological Resources

Bryophytes are among the most neglected yet ecologically significant groups of terrestrial plants. They occupy habitats ranging from tropical forests and montane ecosystems to wetlands, tundra and urban environments. Their capacity to absorb and retain water, intercept atmospheric particles and respond rapidly to environmental changes makes them valuable ecological indicators (Glime, 2007).

Mosses and liverworts can accumulate atmospheric pollutants and heavy metals, making them useful in biomonitoring programmes (Rühling and Tyler, 1968). Their biological responses can provide information about air quality, atmospheric deposition and ecosystem disturbance.

The phytochemical potential of bryophytes is another major research frontier. Liverworts are particularly known for producing characteristic terpenoids and aromatic compounds, many of which exhibit antimicrobial, antifungal, antioxidant and cytotoxic activities (Asakawa et al., 2013). Ethnomedicinal studies have documented the traditional use of bryophytes for skin disorders, wound healing, fever and infections, indicating opportunities for systematic pharmacological investigation (Singh et al., 2016).

Recent research has further emphasized the ethnobotanical and ecological importance of bryophytes and their potential applications in medicine and cosmeceuticals (Chetia et al., 2025). However, many species remain chemically uncharacterized.

Promising research areas

- Bioactive metabolite discovery.
- Antibacterial and antifungal screening.
- Antioxidant and anti-inflammatory investigations.
- Anticancer compound discovery.
- Cosmeceutical development.
- Heavy-metal biomonitoring.
- Carbon and nitrogen cycling.
- Desiccation tolerance mechanisms.
- Moss-based environmental sensors.
- Tissue culture and micropropagation.

The combination of metabolomics and molecular biology may reveal novel compounds that cannot be detected through conventional screening alone.

5. Pteridophytes as Evolutionary Models and Sources of Novel Bioactive Molecules

Pteridophytes represent an important stage in plant evolution characterized by vascular tissue but reproduction through spores rather than seeds. Ferns and lycophytes therefore provide valuable models for studying the evolution of vascular systems, leaf development, reproductive biology and plant–environment interactions (Ranker and Sundue, 2015).

Their biological importance extends to traditional medicine. Numerous fern species have been used in ethnomedicine for treating infections, inflammation, wounds and gastrointestinal disorders. These traditional applications provide a valuable starting point for pharmacological research.

Pteridophytes synthesize diverse classes of secondary metabolites, including flavonoids, phenolics, terpenoids and other specialized compounds. These molecules may exhibit antioxidant, antimicrobial, anti-inflammatory and cytotoxic properties. However, the chemical investigation of pteridophytes remains much less developed than that of angiosperms.

A major opportunity lies in the systematic screening of pteridophyte species from biodiversity hotspots. The Western Ghats of India, for example, contain diverse fern and fern-allies habitats, but many species remain inadequately studied for their pharmacological and industrial potential.

Future research should integrate:

- Morphological identification.
- DNA barcoding.
- Phytochemical profiling.
- GC–MS and LC–MS analysis.
- HPLC fingerprinting.
- Antimicrobial assays.
- Antioxidant assays.
- Molecular docking.

- Cell-based pharmacological assays.
- Toxicological evaluation.

Such research could establish a pipeline from species discovery → metabolite identification → biological validation → product development.

6. Algae and Cyanobacteria: The Blue-Green Frontier of Primitive Botany

Algae represent one of the most promising components of primitive botany from an applied perspective. Their rapid growth, photosynthetic efficiency and biochemical diversity have generated extensive interest in biotechnology.

Microalgae can produce proteins, carbohydrates, lipids, pigments, vitamins and bioactive compounds. Species belonging to genera such as Chlorella, Spirulina and Dunaliella have been explored for nutritional and industrial applications (Pulz and Gross, 2004; Borowitzka, 2013).

Algal pigments, including chlorophylls, carotenoids and phycobiliproteins, have applications in food, cosmetics, pharmaceuticals and nutraceuticals. Algal polysaccharides are being investigated as functional biomaterials and pharmaceutical ingredients (Wells et al., 2017).

The biofuel potential of microalgae has also received considerable attention because of their ability to accumulate lipids under suitable conditions. However, economic challenges related to cultivation, harvesting and downstream processing remain important barriers to commercialization (Chisti, 2007).

Another emerging field is algal bioremediation. Algae can remove nutrients and certain pollutants from wastewater while simultaneously generating biomass that may have further applications. This integrated approach could support circular bioeconomy models.

Future research should focus on:

- High-value metabolites before bulk biofuel production.
- Genetic improvement of productive strains.
- Stress-induced metabolite production.
- Algal biorefineries.
- Wastewater-based cultivation.
- Carbon dioxide capture.
- Pharmaceutical screening.
- Functional foods.
- Biodegradable biomaterials.

Thus, algae may become one of the most important biological platforms for sustainable industrial development.

7. Primitive Plants as Reservoirs of Novel Phytochemicals

One of the most compelling reasons to intensify research on primitive botanical groups is their largely unexplored chemical diversity. Plants produce specialized metabolites as ecological adaptations to herbivory, microbial attack, UV radiation, competition and environmental stress.

Bryophytes are particularly notable for unique terpenoids and aromatic compounds, whereas ferns contain phenolics, flavonoids and other specialized metabolites (Asakawa et al., 2013; Singh et al., 2016). Algae produce structurally diverse polysaccharides, pigments, lipids and secondary metabolites with pharmaceutical and industrial potential (Wells et al., 2017).

The application of metabolomics can accelerate discovery by generating comprehensive chemical fingerprints. LC–MS/MS, GC–MS, NMR spectroscopy and molecular networking can be used to identify known and unknown metabolites.

A promising research strategy is the integration of:

Taxonomy + Metabolomics + Bioactivity + Molecular Biology + Computational Chemistry

This approach can reduce the gap between traditional botanical collections and modern drug discovery.

However, chemical discovery must be accompanied by rigorous validation. Extract-based claims should be supported by compound isolation, structural characterization, dose-response studies, mechanism-of-action investigations and toxicity assessments.

8. Ethnobotany and Indigenous Knowledge: An Underutilized Research Gateway

Traditional knowledge represents a valuable starting point for identifying biologically active organisms. Indigenous communities often possess detailed knowledge of plants that may not yet have attracted scientific attention.

Ethnomedicinal information regarding bryophytes and pteridophytes has demonstrated that these groups have been used for diverse health conditions (Singh et al., 2016). Such knowledge can guide researchers toward species with potentially useful biological properties.

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However, ethnobotanical research must be conducted ethically. Indigenous knowledge should not be treated merely as a source of information for commercial exploitation. Research should involve prior informed consent, recognition of knowledge holders, benefit sharing and compliance with biodiversity regulations.
The integration of ethnobotany with modern analytical methods could establish an ethnobotany-to-pharmacology pipeline, in which traditional use guides species selection, followed by phytochemical characterization, biological screening and clinical validation.
Such an approach can simultaneously support:
- Traditional knowledge preservation.
- Drug discovery.
- Community participation.
- Biodiversity conservation.
- Sustainable livelihood development.

The future of ethnobotanical research should therefore be collaborative rather than extractive.

9. The Research Gap: Why Is There Still a Thirst for Research?
Despite the enormous potential of primitive botanical groups, several limitations continue to restrict research progress.

9.1 Taxonomic neglect
Many species remain poorly documented, and taxonomic expertise is declining.

9.2 Limited molecular resources
Compared with major crop plants, genomic resources for many bryophytes and pteridophytes remain limited.

9.3 Insufficient phytochemical exploration
A large proportion of species have never undergone systematic metabolomic investigation.

9.4 Fragmented research
Taxonomy, ecology, chemistry and biotechnology are often conducted independently rather than through integrated projects.

9.5 Lack of commercialization pathways
Discoveries frequently remain at the laboratory stage without progressing toward product development.

9.6 Conservation challenges
Research collections must be balanced against the need to protect natural populations.

9.7 Declining expertise
Classical taxonomic skills are essential but increasingly underrepresented in modern curricula and research programmes.
These gaps demonstrate that the "thirst" for research is not simply a shortage of publications. It is a shortage of integrated, translational and interdisciplinary research frameworks.

10. Future Research Priorities and Strategic Roadmap
The future development of primitive botany should be based on a coordinated research strategy.

Priority 1: Biodiversity documentation
Large-scale surveys should be conducted in biodiversity hotspots, especially poorly explored microhabitats.

Priority 2: Molecular authentication
DNA barcoding and genomic approaches should be integrated with traditional taxonomy.

Priority 3: Bioactive compound discovery
Metabolomic and pharmacological investigations should target poorly studied species.

Priority 4: Climate resilience
Desiccation, heat, salinity and drought tolerance mechanisms should be investigated.

Priority 5: Environmental applications
Research should focus on biomonitoring, phytoremediation and ecological restoration.

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Priority 6: Conservation biotechnology
Tissue culture, cryopreservation and DNA banking should be expanded for threatened species.

Priority 7: Digital botany
AI and machine learning should be used for identification, distribution modelling and biodiversity prediction.

Priority 8: Sustainable bioeconomy
Research should prioritize high-value products such as pharmaceuticals, nutraceuticals, pigments, cosmetics and biomaterials.

Priority 9: Indigenous knowledge
Ethnobotanical knowledge should be documented through ethical and participatory frameworks.

Priority 10: Interdisciplinary research
Botanists should collaborate with microbiologists, chemists, pharmacologists, bioinformaticians, environmental scientists and engineers.
The ultimate objective should be the establishment of Primitive Plant Bio innovation Centers that combine biodiversity exploration, taxonomy, molecular biology, phytochemistry, biotechnology and conservation.

11. Conclusion
Primitive botanical groups should no longer be regarded as peripheral subjects of academic botany. Algae, bryophytes and pteridophytes represent evolutionarily distinctive and biologically sophisticated lineages that contain enormous unexplored potential. Their importance extends from understanding the origin and diversification of plant life to addressing contemporary challenges in medicine, agriculture, environmental remediation, climate adaptation and sustainable biotechnology.
The scientific evidence demonstrates that bryophytes contribute to ecosystem functioning, environmental monitoring and the discovery of biologically active metabolites; pteridophytes provide important evolutionary models and promising phytochemical resources; and algae constitute highly versatile platforms for food, pharmaceutical, industrial and environmental biotechnology (Glime, 2007; Asakawa et al., 2013; Ranker and Sundue, 2015; Wells et al., 2017). Recent attention to the ethnobotanical significance of bryophytes further emphasizes that substantial biological and cultural knowledge remains to be explored (Chetia et al., 2025).
The greatest challenge is therefore not the absence of biological resources but the absence of sufficiently integrated research. The future demands a transition from descriptive botany toward discovery-driven, molecularly informed and application-oriented research. Classical taxonomy must be combined with DNA barcoding, omics, metabolomics, artificial intelligence, tissue culture and advanced biotechnology. At the same time, scientific exploration must remain firmly connected to biodiversity conservation, ethical bioprospecting and equitable benefit sharing.
The phrase "thirst of research" can thus be interpreted as a call to rediscover the scientific value of neglected botanical diversity. Every unexplored species represents not merely a taxonomic entry but a potential source of genes, metabolites, ecological functions and evolutionary knowledge. In an era of climate change, biodiversity loss and increasing demand for sustainable resources, the renewed exploration of primitive botanical groups may provide solutions that conventional biological research has overlooked. The future of primitive botany lies in transforming forgotten biodiversity into validated knowledge, validated knowledge into sustainable innovation, and sustainable innovation into conservation and societal benefit.

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