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Azolla as a Multifunctional Bioresource in Climate-Smart Agriculture and the Circular Bio-Economy: A Comprehensive Review

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ABSTRACT

Agriculture faces the dual challenge of ensuring food security for a growing global population while minimizing environmental degradation associated with intensive production systems. Modern crop production is heavily dependent on synthetic fertilizers, particularly nitrogen (N) fertilizers, whose manufacture is energy-intensive and whose inefficient utilization contributes significantly to greenhouse gas (GHG) emissions, soil degradation, eutrophication, and groundwater contamination. Global nitrogen-use efficiency (NUE) in cereal production remains below 50%, indicating substantial nutrient losses to the environment. Consequently, sustainable alternatives that improve nutrient cycling and reduce dependence on chemical fertilizers have gained increasing attention.

Azolla, a free-floating aquatic fern belonging to the family Salviniaceae, has emerged as a promising multifunctional bioresource for sustainable agriculture. Its symbiotic association with the nitrogen-fixing cyanobacterium *Anabaena azollae* enables continuous biological nitrogen fixation, allowing Azolla to accumulate substantial quantities of biomass and biologically fixed nitrogen within a short period. Beyond its traditional role as a green manure in rice-based cropping systems, recent research highlights its multifunctional applications as a biofertilizer, livestock feed supplement, phytoremediation agent, carbon sequestration tool, and component of circular bioeconomy models.

Studies indicate that Azolla can contribute 30–60 kg N ha^{-1} per crop cycle, reduce synthetic nitrogen fertilizer requirements by 25–60%, improve soil organic carbon and microbial activity, and enhance nutrient-use efficiency in rice ecosystems. Owing to its high crude protein content (20–35% dry weight), essential amino acids, vitamins, and minerals, Azolla has also gained importance as an alternative feed resource for dairy cattle, poultry, small ruminants, and aquaculture systems. Furthermore, Azolla demonstrates remarkable potential in wastewater treatment through nutrient recovery and heavy metal sequestration. Recent investigations have also highlighted its role in mitigating methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) emissions from agricultural systems.

This review synthesizes current knowledge on Azolla biology, agronomic applications, environmental benefits, livestock feeding potential, climate-smart agriculture, and circular bioeconomy opportunities.

Keywords: Azolla, Biological nitrogen fixation, Biofertilizer, Sustainable agriculture

INTRODUCTION

Global Fertilizer Consumption

The global agricultural sector relies heavily on mineral fertilizers to sustain crop productivity and ensure food security for a rapidly growing population. Global fertilizer consumption currently exceeds 190 million tonnes of nutrients annually, with nitrogen fertilizers accounting for nearly 60% of total nutrient use (FAO, 2022; IFA, 2023). The widespread adoption of synthetic fertilizers following the Green Revolution substantially increased crop yields and contributed significantly to global food production (Erisman et al., 2008). However, the manufacture of nitrogen fertilizers through the Haber-Bosch process is highly energy-intensive and consumes approximately 1–2% of the world's total energy supply while contributing significantly to anthropogenic carbon dioxide emissions (Smil, 2001; Zhang et al., 2015).

The continuous and often excessive application of chemical fertilizers has resulted in nutrient imbalances, soil degradation, groundwater contamination, eutrophication of aquatic ecosystems, and increased greenhouse gas emissions (Sutton et al., 2011; Pretty et al., 2018). In Asia, particularly in rice-growing regions of India, China, Bangladesh, Vietnam, and the Philippines, fertilizer consumption has increased

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dramatically over the last five decades (Ladha et al., 2022). India is currently one of the largest consumers of nitrogen fertilizers globally, with urea representing the dominant source of nitrogen in agricultural production systems (FAOSTAT, 2024).

Nitrogen-Use Efficiency Crisis

Nitrogen is the nutrient most frequently limiting crop productivity worldwide. Despite large-scale fertilizer application, only a fraction of the applied nitrogen is effectively utilized by crops. Global nitrogen-use efficiency (NUE) in cereal production systems generally ranges between 30% and 50%, while the remaining nitrogen is lost through ammonia volatilization, nitrate leaching, surface runoff, and denitrification processes (Raun and Johnson, 1999; Lassaletta et al., 2014).

These losses impose substantial economic and environmental costs. Nitrate contamination threatens groundwater quality and public health, while nutrient enrichment of rivers and lakes contributes to eutrophication and biodiversity loss (Galloway et al., 2008). Agricultural soils are also major sources of nitrous oxide (N_2O), a greenhouse gas with a global warming potential approximately 273 times greater than carbon dioxide over a 100-year time horizon (IPCC, 2023). Consequently, improving nitrogen-use efficiency has become a major global priority for sustainable agricultural development (Ladha et al., 2005; Zhang et al., 2021).

Integrated nutrient management strategies that combine biological and inorganic nutrient sources are increasingly recognized as viable approaches to reducing nitrogen losses while maintaining crop productivity (Roobroeck et al., 2015).

Climate Change and Sustainable Intensification

Agriculture occupies a central position in the climate change-food security nexus. Climate change is already affecting agricultural productivity through rising temperatures, changing rainfall patterns, increased frequency of droughts and floods, and heightened incidence of pests and diseases (IPCC, 2023). At the same time, agriculture contributes approximately 22–24% of global anthropogenic greenhouse gas emissions through fertilizer use, rice cultivation, livestock production, and land-use change (Crippa et al., 2021).

To address these challenges, the concept of sustainable intensification has gained considerable attention. Sustainable intensification aims to increase agricultural production while minimizing environmental impacts and conserving natural resources (Pretty et al., 2018). Key principles include enhancing resource-use efficiency, improving soil health, reducing external input dependence, increasing biodiversity, and strengthening resilience to climate variability (Rockström et al., 2017).

Nature-based agricultural solutions are increasingly viewed as essential components of climate-smart agriculture because they simultaneously improve productivity, adaptation, and mitigation outcomes (FAO, 2013). Biological nitrogen fixation technologies, green manures, cover crops, and biofertilizers are therefore receiving renewed scientific and policy interest worldwide (Herridge et al., 2008).

Role of Biological Inputs in Sustainable Agriculture

Biological inputs such as biofertilizers, microbial inoculants, composts, green manures, and biostimulants play an increasingly important role in sustainable farming systems by improving nutrient availability, enhancing soil biological activity, and reducing dependence on synthetic fertilizers (Vessey, 2003; Bhardwaj et al., 2014).

Among these biological resources, Azolla occupies a unique position because of its symbiotic association with the nitrogen-fixing cyanobacterium Anabaena azollae. This symbiosis enables continuous atmospheric nitrogen fixation and rapid biomass accumulation under suitable environmental conditions (Peters and Meeks, 1989; Lumpkin and Plucknett, 1980). Under tropical conditions, Azolla can double its biomass within 3–10 days and contribute between 30 and 60 kg N ha^{-1} per rice crop cycle, substantially reducing the requirement for synthetic nitrogen fertilizers (Watanabe and Liu, 1992; Wagner, 1997).

When incorporated into soil, Azolla decomposes rapidly due to its low carbon-to-nitrogen ratio, releasing nutrients that become readily available for crop uptake (Cissé and Vlek, 2003). Numerous studies have demonstrated that Azolla incorporation improves soil organic carbon, microbial biomass, nutrient availability, and rice productivity while suppressing weeds and reducing ammonia volatilization losses (Shin et al., 2021; Chandrababu and Parvathy, 2025; Yang et al., 2025).

In recent years, the role of Azolla has expanded beyond its traditional use as green manure. Emerging evidence indicates that Azolla can serve as a high-protein livestock feed, a phytoremediation agent for wastewater treatment, a carbon sequestration tool, and a key component of circular bioeconomy systems (Munaro, 2025; Korsa et al., 2024). These multifunctional attributes position Azolla as a strategic biological input capable of contributing to sustainable intensification, climate-smart agriculture, and regenerative farming systems.

Taxonomy and Biology of Azolla

Taxonomy and Species Diversity

Azolla is a genus of free-floating aquatic ferns belonging to the family Salviniaceae and order Salviniales (Fig. 1). The genus is unique among pteridophytes because of its symbiotic association with the nitrogen-fixing cyanobacterium *Anabaena azollae* (currently classified as Trichormus azollae by some taxonomists), which resides within specialized cavities of the dorsal leaf lobes (Peters and Meeks, 1989; Wagner, 1997).

Fig. 1: Azolla

Based on morphological, cytological, and molecular studies, six extant species of Azolla are generally recognized worldwide (Lumpkin and Plucknett, 1980; Metzgar et al., 2007) (Table 1):

Table 1: Major species of Azolla and their distribution

Species	Major Distribution	Important Characteristics
Azolla pinnata	Asia, Australia, Africa	Most widely cultivated in rice ecosystems
Azolla filiculoides	Europe, North and South America	High adaptability and cold tolerance
Azolla microphylla	Tropical and subtropical regions	Rapid biomass production
Azolla mexicana	Central and North America	Moderate growth under warm conditions
Azolla caroliniana	North and South America	Good phytoremediation potential
Azolla nilotica	Eastern and Central Africa	Largest species with extensive root system

Recent molecular phylogenetic studies using chloroplast DNA markers have improved understanding of species relationships and evolutionary history within the genus (Metzgar et al., 2007; Li et al., 2018). The remarkable evolutionary success of *Azolla* is attributed to its rapid vegetative propagation, efficient nutrient acquisition, and stable nitrogen-fixing symbiosis.

Morphology

Azolla is a small floating freshwater fern typically measuring 1–5 cm in diameter. The plant body consists of a short, highly branched rhizome bearing numerous overlapping bilobed leaves and adventitious roots that hang freely in water (Wagner, 1997) (Fig. 2).

Each leaf is divided into:

1. **Dorsal (upper) lobe**
   - Photosynthetic region.
   - Contains cavities housing *Anabaena azollae*.
   - Often exhibits green, reddish, or purple coloration depending on environmental conditions.
2. **Ventral (lower) lobe**
   - Thin and partially submerged.
   - Facilitates nutrient and water absorption.

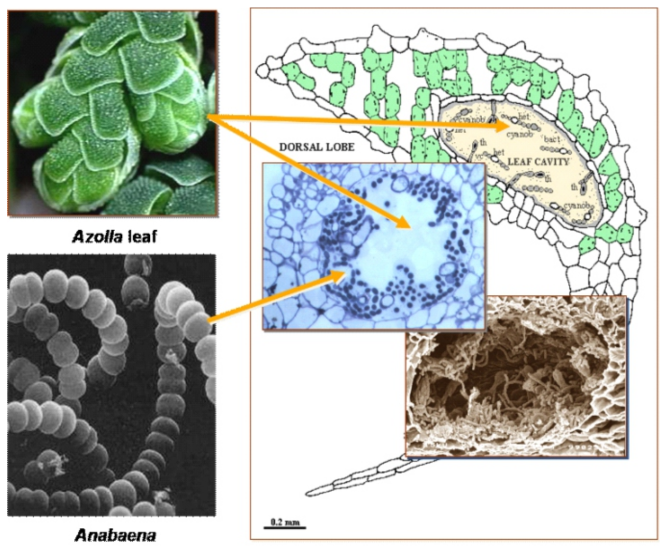

Fig. 2: Azolla's dorsal leaf cavities provide a home for Anabaena (Carrapiço, 2010).

The root system is relatively simple and consists of a single unbranched adventitious root emerging from each node. Reproduction occurs both vegetatively through fragmentation and sexually through sporocarps containing microspores and megaspores (Lumpkin and Plucknett, 1980). The compact growth habit enables Azolla to form dense mats on water surfaces, reducing light penetration and suppressing weed emergence in flooded rice fields (Wagner, 1997).

Geographic Distribution and Ecological Adaptation

Azolla is naturally distributed across tropical, subtropical, and temperate regions of the world. It occurs in ponds, canals, lakes, wetlands, rice paddies, and slow-moving freshwater ecosystems (Lumpkin and Plucknett, 1980) (Table 2).

Table 2: Ecological Requirements for Optimum Growth of Azolla

Parameter	Optimum Range
Temperature	20–30°C
Water pH	5.0–7.5
Relative humidity	>70%
Water depth	5–15 cm
Phosphorus concentration	Moderate to high
Light intensity	Partial to full sunlight

Among the species, *A. pinnata* dominates Asian rice-growing regions, including India, China, Bangladesh, Vietnam, and the Philippines. The fern thrives under flooded conditions and exhibits rapid biomass doubling within 3–10 days under optimal nutrient availability (Wagner, 1997; Peters and Meeks, 1989).

In India, *Azolla pinnata* has been widely promoted for rice cultivation, integrated farming systems, dairy enterprises, and natural farming initiatives because of its adaptability to tropical climatic conditions (Chandrababu and Parvathy, 2025).

Symbiosis with *Anabaena azollae*

The most remarkable biological feature of *Azolla* is its obligate symbiotic relationship with the cyanobacterium *Anabaena azollae*. The cyanobacterium occupies specialized leaf cavities and supplies biologically fixed nitrogen directly to the host fern (Peters and Meeks, 1989).

Unlike most plant-microbe associations, the *Azolla–Anabaena* symbiosis is vertically transmitted from one generation to the next through reproductive structures, ensuring long-term stability of the association (Carrapiço, 2017).

The symbiotic relationship functions as follows:

- The fern supplies carbohydrates and a protected environment.
- *Anabaena* fixes atmospheric nitrogen through specialized heterocyst cells.
- Fixed nitrogen is transferred to the fern as ammonium and amino compounds.
- The fern utilizes this nitrogen for rapid growth and biomass accumulation.

This highly efficient partnership enables *Azolla* to accumulate substantial amounts of nitrogen-rich biomass without external nitrogen fertilization, making it one of the most productive biological nitrogen-fixing systems known in agriculture (Peters and Meeks, 1989).

Nitrogen Fixation Mechanisms in Azolla

Biological Nitrogen Fixation and the Nitrogenase Pathway

Biological nitrogen fixation (BNF) is the enzymatic conversion of atmospheric nitrogen (N_2) into ammonia (NH_3), which can be assimilated by living organisms. In *Azolla*, this process is carried out exclusively by *Anabaena azollae* through the enzyme complex nitrogenase (Peters and Meeks, 1989).

The overall reaction can be expressed as:

$N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16Pi$

The nitrogenase enzyme consists of:

- Dinitrogenase reductase (Fe protein)
- Dinitrogenase (MoFe protein)

Because nitrogenase is highly sensitive to oxygen, nitrogen fixation occurs within specialized heterocysts that maintain a low-oxygen microenvironment suitable for enzyme activity (Bothe et al., 2010). Fixed nitrogen is rapidly incorporated into amino acids such as glutamine and glutamate before being transferred to the host fern.

Environmental Factors Controlling Nitrogen Fixation

Nitrogen fixation rates in *Azolla* are strongly influenced by environmental conditions.

Temperature

Optimum nitrogen fixation generally occurs between 20 and 30°C. Temperatures above 35°C reduce growth and heterocyst activity, while prolonged exposure above 40°C may cause severe biomass decline (Lumpkin and Plucknett, 1980).

Phosphorus Availability

Phosphorus is often the most limiting nutrient for *Azolla* growth and nitrogen fixation because ATP generation during nitrogen fixation requires substantial phosphorus availability (Wagner, 1997).

Light Intensity

Adequate light promotes photosynthesis and carbohydrate supply to the cyanobiont. Excessive shading significantly reduces biomass accumulation and nitrogenase activity.

Water Chemistry

Optimum performance occurs under slightly acidic to neutral conditions (pH 5.0–7.5). Salinity, heavy metal contamination, and nutrient deficiencies can negatively affect symbiotic efficiency.

Quantification of Nitrogen Fixation

Several methods are used to quantify nitrogen fixation in *Azolla* systems.

Acetylene Reduction Assay (ARA)

The most widely used indirect method measures the reduction of acetylene (C_2H_2) to ethylene (C_2H_4) by nitrogenase activity. It provides a rapid estimate of nitrogen fixation rates (Hardy et al., 1968).

^{15}N Isotope Dilution Technique

This method directly quantifies biological nitrogen fixation through stable isotope tracing and is considered one of the most accurate approaches (Kumarasinghe et al., 1993).

Total Nitrogen Accumulation Method

Nitrogen fixation can also be estimated by measuring total nitrogen accumulation in Azolla biomass over time.

Molecular Approaches

Recent studies utilize molecular markers such as nifH genes and transcriptomic analyses to evaluate nitrogen-fixing activity under varying environmental conditions (Li et al., 2018).

Global Estimates of Nitrogen Fixation by Azolla

The *Azolla–Anabaena* symbiosis is considered among the most efficient biological nitrogen-fixing systems in agriculture. Depending on species, environmental conditions, and management practices, *Azolla* can contribute substantial quantities of biologically fixed nitrogen (Table 3).

Table 3: Nitrogen Contribution of Azolla in Rice Fields

Azolla use	Nitrogen contributed (kg N ha^{-1})	Reference
Green manure before transplanting	30–60	Marzouk et al. (2023); IRRI (n.d.)
Dual cropping with rice	40–60	Marzouk et al. (2023)
Green manure + dual cropping	64–94	Singh and Singh (1987)
One basal crop + two intercrops	83–92 (IR-36), 65–70 (Mahsuri)	Singh et al. (1988)

Under favourable conditions, annual nitrogen accumulation may exceed 300 kg N ha^{-1} through repeated biomass production cycles, significantly reducing dependence on synthetic nitrogen fertilizers in rice-based systems (Wagner, 1997).

Agronomic Applications of *Azolla*

Azolla in Rice Production Systems

The most widely documented agronomic application of *Azolla* is in lowland rice cultivation. Owing to its rapid growth, high nitrogen-fixing capacity, and compatibility with flooded conditions, *Azolla* has been extensively used as a green manure and dual crop in rice ecosystems. The symbiotic association between *Azolla* and *Anabaena azollae* can contribute approximately 30–60 kg N ha^{-1} per crop cycle, thereby reducing dependence on synthetic nitrogen fertilizers (Peters and Meeks, 1989; Wagner, 1997).

Two principal approaches are employed in rice cultivation:

1. Basal incorporation: *Azolla* biomass is grown prior to transplanting and incorporated into the soil.
2. Dual cropping: *Azolla* is cultivated simultaneously with rice and incorporated during crop growth (Fig. 3 & 4).

Several studies have reported that incorporation of *Azolla* biomass significantly improves rice growth, nitrogen uptake, and grain yield. Under favorable conditions, substitution of 25–50% of mineral nitrogen fertilizer with *Azolla* has maintained or enhanced rice productivity while reducing fertilizer costs (Watanabe and Liu, 1992; Cissé and Vlek, 2003).

Fig. 3: Azolla cultivation

Fig. 4: Dual cropping system: azolla with rice

Besides nitrogen supply, *Azolla* suppresses weed emergence by forming a dense floating mat that reduces light penetration and limits weed germination. Furthermore, the fern decreases ammonia volatilization losses from urea-fertilized rice fields, thereby improving nitrogen-use efficiency (Cissé and Vlek, 2003) (Table 4).

Table 4: Benefits of Azolla in Rice Systems

Benefit	Effect
Biological nitrogen fixation	30–60 kg N ha^{-1}
Reduction in fertilizer N requirement	25–50%
Weed suppression	Reduced weed emergence
Improved nitrogen-use efficiency	Reduced NH_3 loss
Increased rice yield	5–20%

Azolla in Rice–Wheat Cropping Systems

The rice–wheat system is one of the most intensive cereal production systems in South Asia. Long-term cultivation has led to declining soil organic matter, nutrient imbalances, and reduced productivity in many regions of the Indo-Gangetic Plains (Ladha et al., 2003).

Incorporation of *Azolla* during the rice phase provides additional organic matter and biologically fixed nitrogen that can benefit the succeeding wheat crop. Following decomposition, *Azolla* releases nitrogen and other nutrients, thereby improving soil fertility and reducing nutrient mining from agricultural soils (Wagner, 1997). The inclusion of biological nutrient sources such as *Azolla* in rice–wheat systems supports integrated nutrient management strategies aimed at improving nutrient-use efficiency and long-term sustainability (Ladha et al., 2005). Repeated organic matter additions contribute to improved soil physical, chemical, and biological properties, which are essential for maintaining productivity in intensive cereal systems.

Azolla in Rice–Pulse Systems

Rice–pulse systems are increasingly recognized as sustainable alternatives to continuous cereal-based cropping because pulses contribute biologically fixed nitrogen and improve soil fertility (Peoples et al., 2009). Incorporation of *Azolla* during the rice phase further enhances nutrient cycling and organic matter accumulation. Following decomposition, *Azolla* biomass releases readily available nitrogen and contributes organic substrates that stimulate microbial activity. Improved nutrient availability can support establishment and growth of subsequent pulse crops such as mungbean, lentil, blackgram, chickpea, and grass pea. The combined contribution of nitrogen fixation by *Azolla* and legumes provides opportunities to reduce dependence on synthetic fertilizers while maintaining system productivity. Such integrated biological approaches are increasingly important for sustainable intensification of cropping systems (Peoples et al., 2009; Singh et al, 2011).

Azolla in Natural Farming Systems

Natural farming emphasizes biological nutrient cycling, ecological sustainability, and reduced reliance on synthetic inputs. In this context, *Azolla* has emerged as a valuable biological resource because of its capacity to produce nitrogen-rich biomass without external nitrogen fertilization (Wagner, 1997).

The rapid growth rate of *Azolla*, combined with its low carbon-to-nitrogen ratio, allows rapid decomposition and nutrient release following incorporation into soil. Consequently, it serves as an effective green manure in organic and natural farming systems. Furthermore, *Azolla* can be integrated with livestock enterprises as a feed supplement and with composting systems as an organic nutrient source. Such multifunctional applications contribute to nutrient recycling and support circular farming systems that emphasize internal resource use efficiency.The increasing emphasis on regenerative agriculture, climate-smart agriculture, and natural farming has renewed interest in the utilization of *Azolla* as a low-cost and environmentally friendly biological input. The rapid decomposition of *Azolla* biomass, combined with its low C:N ratio (approximately 10–15), facilitates quick nutrient release and improves nutrient-use efficiency (Wagner, 1997). Additionally, integration of *Azolla* with farmyard manure, vermicompost, and microbial inoculants can strengthen soil biological processes and reduce external fertilizer requirements. In diversified farming systems, *Azolla* contributes to circular nutrient flows by linking crop, livestock, and aquatic production components. Such multifunctional roles make *Azolla* particularly suitable for climate-resilient and resource-conserving agricultural systems.

Soil Health Enhancement through Azolla

Improvement in Soil Organic Carbon

Soil organic carbon (SOC) is widely recognized as a key indicator of soil health because it influences nutrient retention, water-holding capacity, aggregate stability, and biological activity (Lal, 2004). Incorporation of *Azolla* biomass contributes organic matter to soil and promotes carbon accumulation through decomposition processes.

The repeated addition of organic residues enhances SOC concentrations and improves soil quality. Because *Azolla* possesses a relatively low C:N ratio compared with cereal residues, decomposition occurs rapidly and contributes readily available carbon substrates to soil microbial communities (Wagner, 1997). Increased SOC enhances nutrient retention, improves soil structure, and contributes to long-term sustainability of intensive cropping systems (Lal, 2004).

Microbial Biomass Carbon

Microbial biomass carbon (MBC) represents the living component of soil organic matter and serves as a sensitive indicator of changes in soil biological activity (Jenkinson and Ladd, 1981).

The incorporation of *Azolla* biomass provides labile carbon and nitrogen substrates that stimulate microbial growth and activity. Enhanced microbial biomass contributes to accelerated nutrient mineralization, decomposition of organic matter, and nutrient transformation processes. Organic amendments such as green manures have consistently been shown to increase microbial biomass and improve soil biological functioning compared with sole reliance on mineral fertilizers (Haynes and Beare, 1997). Therefore, *Azolla* incorporation can play an important role in improving soil biological quality in rice-based production systems.

Soil Enzyme Activities

Soil enzymes are responsible for mediating key biochemical processes associated with carbon, nitrogen, phosphorus, and sulfur cycling. Activities of enzymes such as dehydrogenase, urease, phosphatase, and β-glucosidase are commonly used as indicators of soil biological health (Dick, 1994).

Organic matter additions generally increase enzyme activity by supplying energy and nutrients to soil microorganisms. Because *Azolla* biomass decomposes rapidly and provides readily available substrates, incorporation of the fern can stimulate microbial metabolism and associated enzyme activities. Enhanced enzyme activity improves nutrient mineralization and facilitates the conversion of organic nutrients into plant-available forms, thereby supporting crop productivity and nutrient-use efficiency.

Aggregate Stability and Soil Physical Properties

Soil aggregation is essential for maintaining favorable soil structure, water infiltration, aeration, and root development. Soil organic matter plays a critical role in aggregate formation by acting as a binding agent between mineral particles (Six et al., 2004).

The addition of organic materials such as *Azolla* contributes to aggregate stabilization through increased microbial activity and production of extracellular polysaccharides. Improved aggregate stability enhances soil resistance to erosion and supports sustainable soil management. Long-term improvements in aggregation are particularly important in intensively cultivated rice soils where puddling and continuous cultivation often degrade soil structure.

Nutrient Cycling and Nutrient Availability

One of the most important ecological functions of *Azolla* is its contribution to nutrient cycling. During growth, the fern accumulates substantial quantities of nitrogen, phosphorus, potassium, and micronutrients. Following decomposition, these nutrients are released into the soil and become available for crop uptake (Peters and Meeks, 1989).

Because *Azolla* biomass decomposes rapidly, nutrient release is relatively synchronized with crop demand. This characteristic improves nutrient-use efficiency and reduces losses through leaching, runoff, and volatilization. In addition, organic matter inputs stimulate microbial-mediated nutrient transformations that enhance nutrient availability and retention within agricultural ecosystems (Drinkwater and Snapp, 2007).

Azolla as Livestock and Aquaculture Feed

Nutritional Composition of Azolla

The growing demand for alternative and sustainable feed resources has stimulated considerable interest in *Azolla* as a livestock and aquaculture feed supplement. Owing to its rapid growth, high protein content, balanced amino acid composition, and abundance of vitamins and minerals, *Azolla* has emerged as a promising unconventional feed resource (Lumpkin and Plucknett, 1980; Sood et al., 2012).

The nutritional composition of *Azolla* varies depending on species, environmental conditions, nutrient availability, and stage of growth. On a dry matter basis, crude protein content generally ranges from 20 to 35%, while essential amino acids, carotenoids, vitamins (A, B_{12}, β-carotene), calcium, phosphorus, potassium, iron, and magnesium are present in appreciable quantities (Pillai et al., 2002; Sood et al., 2012) (Fig. 5).

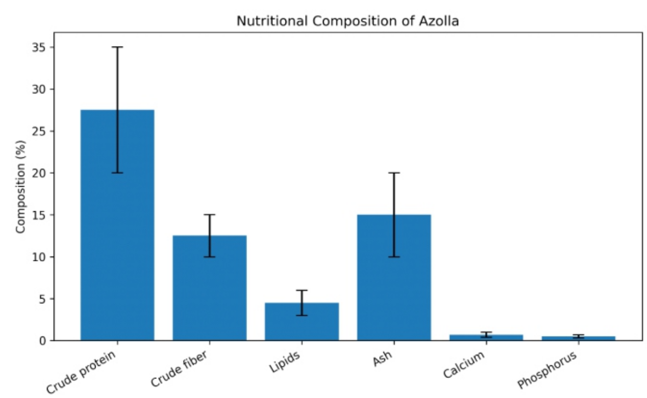

Fig. 5: Typical Nutritional Composition of Azolla (Dry Matter Basis)

The relatively low lignin content and favorable amino acid profile enhance digestibility and make *Azolla* suitable for inclusion in animal feed formulations (Lumpkin and Plucknett, 1980).

Azolla in Dairy Cattle Feeding

Several studies have demonstrated the benefits of supplementing dairy cattle diets with fresh *Azolla*. Due to its high protein content and mineral richness, *Azolla* can partially replace conventional concentrate feeds and reduce feed costs.

Supplementation with *Azolla* has been reported to improve milk yield, milk fat content, and overall animal health in dairy cows and buffaloes (Cherryl et al., 2014). The presence of essential amino acids, carotenoids, and minerals contributes to improved nutrient intake and feed conversion efficiency. In smallholder production systems, incorporation of fresh *Azolla* at 1–2 kg animal^{-1} day^{-1} has been found to be particularly useful where access to high-quality concentrate feed is limited (Pillai et al., 2002).

Azolla in Poultry Nutrition

The poultry industry increasingly seeks alternative feed ingredients to reduce dependence on expensive soybean meal and fish meal. *Azolla* has attracted attention because of its high protein content and abundance of carotenoids.

Research indicates that inclusion of *Azolla* meal at moderate levels in broiler and layer diets can improve growth performance, feed efficiency, egg production, and yolk pigmentation (Alalade and Iyayi, 2006). The carotenoid content enhances yolk color, while the protein and mineral composition contribute to improved productivity. However, excessive inclusion levels may reduce performance due to higher fiber content, emphasizing the need for optimized dietary formulations.

Azolla in Sheep and Goat Production

Small ruminants can effectively utilize *Azolla* as a supplementary protein source. Studies involving sheep and goats have demonstrated improved weight gain, nutrient digestibility, and feed intake when *Azolla* is included as a partial replacement for conventional protein supplements (Reddy et al., 2011; Seethueak et al., 2025). Because *Azolla* can be cultivated on-farm with minimal resource requirements, it represents an economical feed option for resource-poor farmers. Its use may be particularly beneficial during periods of fodder scarcity.

Azolla in Aquaculture

The use of *Azolla* in aquaculture has received increasing attention because of its nutritional quality and rapid biomass production. Fresh and dried *Azolla* have been incorporated into diets for tilapia, carp, and other freshwater fish species.

Studies have shown that partial replacement of commercial feed ingredients with *Azolla* can maintain fish growth performance while reducing feed costs (Hasan and Chakrabarti, 2009). In integrated rice–fish systems, *Azolla* also contributes to nutrient cycling and provides a natural feed source within the aquatic environment. The multifunctional role of *Azolla* in aquaculture aligns well with sustainable and integrated farming approaches.

Azolla in Climate-Smart Agriculture

Methane Mitigation

Flooded rice cultivation is a major source of methane (CH_4) emissions because anaerobic decomposition of organic matter promotes methanogenesis. The incorporation and management of *Azolla* in rice systems can influence methane dynamics through interactions with soil microbial processes. Several studies have reported reductions in methane emissions in rice fields where *Azolla* is integrated with nutrient management practices (Table 5). The fern may alter redox conditions, compete for nutrients, and influence microbial communities involved in methane production and oxidation (Bharati et al., 2000). The integration of biological nutrient sources such as *Azolla* therefore contributes to climate-smart rice production systems.

Nitrous Oxide Reduction

Nitrous oxide (N_2O) is a potent greenhouse gas associated primarily with nitrogen fertilizer use. Because *Azolla* provides biologically fixed nitrogen and improves nitrogen-use efficiency, it has the potential to reduce N_2O emissions relative to systems heavily dependent on synthetic nitrogen fertilizers (Ladha et al., 2005) (Table 5). Improved synchronization between nutrient release from decomposing *Azolla* biomass and crop nitrogen demand may reduce surplus soil nitrogen and associated gaseous losses.

Table 5: Effect of Azolla on Greenhouse Gas Emissions in Rice Ecosystems

Treatment	Reduction in CH_4/N_2O emission	Reference
Dual cropping of Azolla with rice	11.2% CH_4 emission	Liu et al. (2017)
Azolla inoculation with rice	17–33% CH_4 emission	Yang et al. (2019)
Azolla + reduced N fertilizer	27.49% N_2O emission	Malyan et al. (2019)
Rice–Azolla co-cultivation	2.9–13.2% CH_4 and 1.7–8.6% N_2O emission	Yang et al. (2025)
Azolla-Rice system	Up to 36% CH_4 and 76-97% N_2O emission	Candra et al., 2025

Carbon Sequestration

Increasing soil organic carbon is a major strategy for climate change mitigation and soil restoration. Incorporation of *Azolla* biomass contributes organic carbon to soil and supports long-term carbon accumulation through enhanced biological activity and residue inputs (Lal, 2004). The unique evolutionary history of *Azolla* also highlights its significance in global carbon cycling. Geological evidence suggests that large-scale proliferation of *Azolla* during the Eocene contributed substantially to atmospheric carbon sequestration, an event commonly referred to as the "Azolla Event" (Brinkhuis et al., 2006). At the farm level, repeated incorporation of *Azolla* biomass contributes to soil carbon storage and improved ecosystem functioning.

Reduction of Ammonia Volatilization

Ammonia volatilization is one of the major pathways of nitrogen loss from flooded rice systems. Floating *Azolla* mats have been shown to reduce ammonia losses by absorbing ammonium from floodwater and decreasing direct exposure of urea-derived nitrogen to the atmosphere (Cissé and Vlek, 2003). The resulting improvement in nitrogen retention enhances fertilizer-use efficiency and contributes to both economic and environmental sustainability.

Phytoremediation and Circular Bioeconomy

Wastewater Treatment

The remarkable nutrient uptake capacity of *Azolla* has led to increasing interest in its application for wastewater treatment. The fern can rapidly absorb dissolved nitrogen, phosphorus, and other pollutants from agricultural, municipal, and industrial wastewaters (Sood et al., 2012). The rapid growth rate and high nutrient assimilation capacity make *Azolla* a cost-effective biological treatment option for nutrient-rich wastewater streams. In addition to improving water quality, the resulting biomass can be harvested and utilized as feed, fertilizer, or bioenergy feedstock.

Nutrient Recovery

Modern circular economy concepts emphasize the recovery and reuse of nutrients from waste streams. *Azolla* serves as an effective biological nutrient recovery system because it efficiently captures nitrogen and phosphorus from wastewater and converts them into valuable biomass (Brouwer et al., 2018). The harvested biomass can subsequently be recycled into agricultural systems as green manure, livestock feed, compost, or biofertilizer, thereby closing nutrient loops and reducing reliance on synthetic fertilizers.

Heavy Metal Removal

Numerous studies have demonstrated the capacity of *Azolla* species to accumulate heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn) from contaminated water bodies (Costa et al., 2009). The extensive surface area and high adsorption capacity of *Azolla* facilitate metal uptake and sequestration. Consequently, the fern has been investigated as a low-cost phytoremediation agent for industrial effluents and contaminated aquatic environments. However, biomass containing accumulated heavy metals should not be used as feed and requires appropriate disposal or treatment.

Circular Nutrient Loops and Bioeconomy Applications

The concept of a circular bioeconomy seeks to maximize resource efficiency through recycling and reuse of biological materials. *Azolla* is particularly well suited to such systems because it can simultaneously contribute to nutrient recovery, biomass production, feed generation, and soil fertility enhancement (Brouwer et al., 2018).

A typical circular nutrient pathway involves:

Wastewater → Azolla cultivation → Biomass harvesting → Feed/Fertilizer production → Crop and livestock production → Nutrient recycling.

This integrated approach reduces nutrient losses, lowers environmental pollution, and improves resource-use efficiency across agricultural systems. The multifunctional nature of *Azolla* positions it as a valuable component of sustainable bioeconomy strategies aimed at enhancing food security while reducing environmental impacts.

Azolla and the Sustainable Development Goals (SDGs)

Azolla has significant potential to contribute to several United Nations Sustainable Development Goals (SDGs) through its multifunctional roles in agriculture, environmental management, and resource conservation. Its ability to biologically fix atmospheric nitrogen and enhance crop productivity supports SDG 2 (Zero Hunger) by improving food production and reducing dependence on costly synthetic fertilizers (Peters and Meeks, 1989; Wagner, 1997). The capacity of *Azolla* to absorb excess nutrients and pollutants from wastewater and remove heavy metals from contaminated water contributes to SDG 6 (Clean Water and Sanitation) by improving water quality and supporting sustainable wastewater treatment (Sood et al., 2012). Through nutrient recycling, biofertilizer production, livestock feed supplementation, and recovery of nutrients from waste streams, *Azolla* promotes resource-use efficiency and circular bioeconomy principles, thereby supporting SDG 12 (Responsible Consumption and Production) (Brouwer et al., 2018). Its role in reducing fertilizer-related emissions, mitigating methane production in rice fields, lowering ammonia volatilization losses, and enhancing soil carbon sequestration aligns with SDG 13 (Climate Action) by contributing to climate change mitigation and climate-smart agriculture (Bharati et al., 2000; Cissé and Vlek, 2003). Furthermore, by improving soil health, enhancing biodiversity, restoring degraded ecosystems, and reducing environmental pollution, *Azolla* supports SDG 15 (Life on

Land) and promotes sustainable land management. Therefore, the integration of *Azolla* into agricultural and environmental systems offers a practical and nature-based approach for advancing multiple SDGs simultaneously while strengthening global food, water, and environmental security.

CONCLUSION

Azolla is a highly promising aquatic fern with immense potential to contribute to sustainable and climate-resilient agriculture through its unique symbiotic association with the nitrogen-fixing cyanobacterium *Anabaena azollae*. Its ability to fix atmospheric nitrogen, improve soil organic carbon, enhance microbial activity, suppress weeds, reduce fertilizer requirements, and support nutrient cycling makes it an effective biofertilizer for diverse cropping systems, particularly rice-based agriculture. Beyond crop production, *Azolla* serves as a valuable feed resource for livestock and aquaculture due to its high protein and mineral content, while its capacity for wastewater treatment, nutrient recovery, and heavy metal removal highlights its importance in environmental management and circular bioeconomy approaches. Furthermore, its role in mitigating greenhouse gas emissions, reducing ammonia volatilization, and promoting carbon sequestration aligns with the goals of climate-smart agriculture. Although challenges related to large-scale cultivation and adoption remain, continued research and technological advancements can enhance its utilization across agricultural and environmental sectors. Overall, *Azolla* represents a multifunctional, eco-friendly, and economically viable biological resource capable of supporting sustainable intensification, improving resource-use efficiency, and strengthening global food and environmental security.

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