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AZOLLA: A SUSTAINABLE BIOFERTILIZER FOR ENHANCING CROP PRODUCTIVITY – A REVIEW

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Abstract

Azolla, a fast-growing aquatic fern, has gained significant attention as a biofertilizer, particularly for rice and other crops, due to its ability to fix atmospheric nitrogen through its symbiotic association with the cyanobacterium *Anabaena azollae*. Beyond its role in nitrogen fixation, Azolla serves multiple purposes, including use as animal feed, a biogas producer, and a hyperaccumulator of heavy metals. While chemical fertilizers are widely used to enhance crop productivity, their excessive application poses serious environmental and health risks. In contrast, Azolla-based biofertilizers not only enhance crop yield but also contribute to long-term soil fertility and sustainability. Given its diverse applications and eco-friendly nature, the Azolla-*Anabaena* system presents a promising alternative for sustainable agriculture. This review critically evaluates the potential of Azolla as a biofertilizer for improving agricultural sustainability.

Keywords: Azolla, Biofertilizer; Nitrogen Fixation; Sustainable Agriculture; Soil Fertility.

Introduction

In conventional agricultural systems, chemical fertilizers have long been utilized to maximize crop productivity. However, their continuous and excessive application has significantly contributed to environmental degradation, either directly or indirectly (Ali et al., 2021). Over-reliance on synthetic fertilizers has led to soil degradation, water contamination, and adverse effects on plant, animal, and human health. As the global population continues to rise, there is an increasing need for sustainable agricultural practices to ensure food security while minimizing environmental harm (Glick, 2018). Recognizing these concerns, there has been a global shift towards organic farming, which promotes eco-friendly practices to reduce the harmful impact of chemical inputs. Organic farming has gained priority worldwide due to the growing consumer demand for safe, chemical-free food and the need to maintain long-term soil fertility and ecological balance. By minimizing the use of synthetic agrochemicals, organic farming not only ensures food safety but also enhances biodiversity, particularly in soil microbial communities (Megali et al., 2014).

The Role of Biofertilizers in Sustainable Agriculture

Biofertilizers play a crucial role in organic farming by providing essential nutrients through natural processes, such as nitrogen fixation and phosphate solubilization. These formulations contain live microorganisms that, when applied to soil, seeds, or seedlings, enhance nutrient availability and improve plant growth. Biofertilizers contribute to soil fertility by increasing microbial diversity, promoting nutrient assimilation by plants, and even offering protection against plant pathogens through biological control mechanisms (Singh et al., 2021; Santhiya and Jeeva, 2022).

Among biofertilizers, the aquatic fern *Azolla* has emerged as an excellent organic alternative due to its nitrogen-fixing capabilities and diverse agricultural benefits.

Azolla as a Biofertilizer and Green Manure

Azolla, a free-floating aquatic fern, is widely distributed across different climatic regions and has been recognized as a highly effective biofertilizer and green manure. It forms a symbiotic relationship with the nitrogen-fixing cyanobacterium *Anabaena azollae*, allowing it to capture atmospheric nitrogen at an accelerated rate. This remarkable nitrogen-fixing ability makes the *Azolla-Anabaena* system an ideal biofertilizer, particularly for rice cultivation in tropical and subtropical regions (Yadav et al., 2014). One of the key advantages of Azolla is its rapid multiplication rate. Under favorable conditions, it can double its biomass in just a few days, covering the surface of water bodies and forming a dense mat. This mat not only serves as a nitrogen source but also prevents ammonia volatilization, thus minimizing nitrogen loss from agricultural fields. Additionally, Azolla contributes to weed suppression, improves soil organic matter content, and enhances nutrient uptake efficiency in crops. Azolla has been successfully used as a biofertilizer in a variety of crops, including rice, wheat, taro, banana, and tomatoes (York and Garden, 2016). Due to its non-toxic and eco-friendly properties, Azolla is also gaining popularity as a natural fertilizer for household gardening and organic farming (Indrani et al., 2019).

Soil Health and Environmental Benefits of Azolla

The application of Azolla as a biofertilizer offers several advantages beyond nitrogen fixation. It enhances soil fertility by enriching the organic matter content, maintaining optimal pH levels, and increasing the availability of essential nutrients. Furthermore, Azolla acts as a natural source of multiple micronutrients and improves the efficiency of inorganic fertilizers, thereby reducing the dependency on chemical inputs while maintaining or even improving crop yields (Thapa and Poudel, 2021). From an environmental perspective, Azolla serves as an effective tool for sustainable agriculture. It contributes to carbon sequestration, reduces greenhouse gas emissions, and prevents nutrient runoff, which is a major cause of water pollution in conventional farming. Additionally, Azolla functions as a hyperaccumulator, meaning it has the ability to absorb and store heavy metals from contaminated water and soil, thereby playing a significant role in environmental remediation (Mishra and Dash, 2014).

Azolla: Taxonomy, Classification, and Distribution

Introduction

Azolla is a small, free-floating freshwater fern that thrives in tropical and subtropical regions across Asia, Africa, and the Americas (Mishra & Dash, 2014). The name *Azolla* originates from the Greek words *azo* (meaning "to dry") and *allyo* (meaning "to kill"), signifying the plant's inability to survive in dry conditions (Svenson, 1944).

Taxonomy and Classification

The genus *Azolla* was first described by Lamarck in 1783 and was initially classified under the family Salviniaceae within the order Salviniales. However, more recent taxonomic studies have placed *Azolla* in its own distinct monotypic family, Azollaceae (Hills & Gopal, 1967; Konar & Kapoor, 1972).

Currently, seven recognized species of *Azolla* exist within the family Salviniaceae:

1. *Azolla caroliniana* Willd.
2. *Azolla cristata* Kaulf.
3. *Azolla filiculoides* Lam.
4. *Azolla imbricata* (Roxb. ex Griff.) Nakai
5. *Azolla mexicana* C. Presl
6. *Azolla microphylla* Kaulf.
7. *Azolla pinnata* R. Br (IPNI version 1.1)

These species are further categorized into two subgenera: **Euazolla** and **Rhizosperma** (Svenson, 1944). The primary distinguishing feature between these subgenera lies in the structure of their megasporocarps. *Euazolla* species possess three floats in their megasporocarps, whereas *Rhizosperma* species have nine floats. Additionally, trichome morphology plays a key role in species-level identification (Lumpkin & Plucknett, 1982; Nayak & Singh, 1988).

Geographical Distribution

Azolla naturally thrives in freshwater habitats such as ponds, ditches, lakes, and slow-moving rivers in warm-temperate and tropical regions (Fig. 1). However, it is notably absent from areas experiencing prolonged freezing temperatures or extreme aridity, as these environmental conditions hinder its growth and survival (Small & Darbyshire, 2011).

Plate 1. A) *Azolla* sp. habit; B) surface of the paddy field covered by *Azolla* sp.; C) *Azolla* species associated with wetland plants

Habit and Morphology of Azolla

Azolla is a delicate, small-sized aquatic fern with a triangular or polygonal shape. It is primarily free-floating in water bodies but can also grow on moist soil, provided there is sufficient moisture for its survival. The sporophytic plant features a horizontal rhizome, typically ranging from 0.5 to 7 cm in diameter, with numerous branches bearing densely arranged, overlapping leaves. Each leaf is composed of two lobes: a thick **dorsal lobe** and a thin **ventral lobe**, with the dorsal lobe housing a symbiotic blue-green alga, *Anabaena azollae*, responsible for nitrogen fixation (Peters & Mayne, 1974).

The surface of the dorsal lobe is covered by an epidermis that contains vertical rows of single-celled stomata and trichomes, which may consist of one or multiple cells. In contrast, the ventral lobe, which contributes to buoyancy by maintaining contact with water through its convex surface, possesses fewer stomata and trichomes (Eames, 1936). The ventral side also features a multi-branched rhizome that bears small leaves and extends root-like structures into the water, enabling the direct absorption of essential nutrients (Roger, 1999).

Azolla leaves contain chlorophyll for photosynthesis and a colorless lobe that aids in floating. Each lobe has a specialized cavity that creates a micro-environment supporting the symbiotic association between the plant and *Anabaena azollae*. This unique biological relationship facilitates energy exchange and metabolic interactions, allowing Azolla to function as a self-sustaining system within aquatic ecosystems (Adhikari et al., 2020).

Azolla as Green Manure

Azolla has traditionally been cultivated as a green manure for rice cultivation, but it is also beneficial when grown alongside other aquatic crops such as water bamboo (*Zizanica aquatica*), arrowhead (*Sagittaria sagittifolia*), and taro (*Colocasia esculenta*) (Anonymous, 1975). Studies have demonstrated that Azolla application positively impacts rice plant growth, leading to an increase in the number of shoots, the length of the longest leaf, and both fresh and dry biomass (Ngo, 1973). Furthermore, its incorporation into the soil enhances nitrogen levels to an extent comparable to that obtained from leguminous crops like soybeans (Shen et al., 1963). Research indicates that *Azolla filiculoides*, when used as green manure before rice planting, can supply up to 50% of the total nitrogen requirement for the crop (Taller et al., 1977). In another study, incorporating two layers of Azolla into the soil before rice transplantation provided sufficient nitrogen to yield approximately 5 tons of rice per hectare (Tran & Dao, 1973).

For effective application as green manure, Azolla can be harvested directly from water bodies such as ponds and ditches or cultivated in nurseries before being introduced into the field. Within two to three weeks of application, Azolla forms a dense mat on the surface, which can then be incorporated into the soil before rice transplantation. Farmers commonly use single super phosphate (25–50 kg per hectare) in divided applications, though its quantity may be adjusted based on soil phosphorus levels. Additionally, cattle dung or slurry can be used as an alternative to super phosphate. If pests attack the Azolla crop, appropriate pest control measures should be implemented. This method of Azolla application contributes approximately 20–40 kg of nitrogen per hectare (Yadav et al., 2014).

The incorporation of fresh Azolla into the soil significantly improves soil properties, including water-holding capacity, organic carbon content, ammonium nitrogen, nitrate-nitrogen, and available phosphorus, potassium, calcium, and magnesium. It also reduces soil pH and bulk density, contributing to improved soil fertility. Studies show that such incorporation can enhance mung bean yield significantly (Raja et al., 2012).

In a dual-cropping system, Azolla is cultivated alongside rice, with each cycle contributing approximately 30 kg of nitrogen per hectare. Fresh Azolla is introduced 7–10 days after rice transplantation at a rate of 0.5–1.0 tons per hectare. Single super phosphate is applied at a rate of 20 kg per hectare in split doses. Within 15–20 days, Azolla forms a dense mat, which decomposes within 8–10 days, gradually releasing nitrogen into the soil. A second Azolla crop can be grown and incorporated in a similar manner during the rice-growing season. This approach is cost-effective, simple, and highly efficient in terms of biomass production and nitrogen fixation. Moreover, it does not negatively impact rice growth, making it a sustainable and eco-friendly alternative to synthetic fertilizers (Yadav et al., 2014).

Azolla and Soil Nutrient Availability

Azolla possesses an exceptional ability to absorb and retain potassium (K) in its tissues, even in environments where potassium is scarce. As Azolla decomposes, it rapidly releases essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) into the soil after field water drainage, improving soil fertility (Bhuvaneshwari & Singh, 2015). Additionally, Azolla enhances the bioavailability of crucial micronutrients such as zinc (Zn), iron (Fe), and magnesium (Mg), making them more accessible to rice plants. It also releases plant growth regulators and vitamins, which stimulate faster crop growth (Bhusal & Thakur, 2021). Regular application of Azolla contributes to increased soil nutrient levels and fosters beneficial biological activity, leading to a better mineralization process that supports long-term soil health (Subedi & Shrestha, 2015).

When Azolla decomposes, it enriches the soil with phosphorus, making it readily available to plants (Watanabe et al., 1989). Initially, no significant difference in available phosphorus levels was observed in paddy fields treated with Azolla (Rivai et al., 2013). However, at the rice panicle initiation stage, there was an 89% increase in available phosphorus compared to untreated soils. Similarly, phosphorus and calcium levels in Azolla were found to be significantly high, averaging 124.83 ppm and 345.3 mg/100g, respectively (Halder & Kheroar, 2013). Furthermore, soil treated with Azolla demonstrated a 29.12% increase in potassium content, indicating its effectiveness in improving soil fertility and nutrient retention (Dey et al., 2018). These benefits highlight Azolla's potential in integrated soil nutrient management, a crucial aspect often overlooked in many Asian agricultural systems.

Beyond improving nitrogen, phosphorus, and potassium levels, Azolla also plays a key role in increasing organic matter in the soil. It facilitates the release of essential cations such as magnesium (Mg), calcium (Ca), and sodium (Na), which are vital for maintaining soil structure and fertility. The total nitrogen content, available phosphorus, and exchangeable potassium in the soil, along with nitrogen uptake by rice plants, are significantly improved through the application of Azolla (Subedi & Shrestha, 2015). By incorporating Azolla into farming practices, soil fertility is enhanced through increased organic carbon, available nitrogen, and improved macronutrient composition (Mandal et al., 1999).

Furthermore, Azolla application helps in reducing nitrogen losses by curbing ammonia (NH_3) volatilization, which otherwise leads to nitrogen depletion. It also stabilizes soil pH, regulates water temperature, and contributes to the buildup of organic matter. Additionally, Azolla plays a vital role in transforming and enhancing the availability of essential trace elements such as iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu). These factors collectively improve soil structure, promote better infiltration and water movement, and create a more favorable environment for crop growth (Mandal et al., 1999; Pabby et al., 2004).

Overall, the application of Azolla is considered a sustainable agricultural practice for maintaining long-term soil fertility and enhancing crop productivity. Despite some limitations, its integration into farming systems provides numerous benefits, making it a valuable tool for improving soil health and ensuring higher yields (Subedi & Shrestha, 2015).

Effect of Azolla on Soil Organic Matter

Azolla compost plays a significant role in enhancing plant growth and improving crop yield while simultaneously increasing the organic matter content in the soil (Gupta & Potalia, 1990). One of its key advantages is its ability to gradually release its stored nutrients over an extended period. This slow decomposition process makes Azolla more beneficial compared to raw, unprocessed organic materials and chemical fertilizers, which often provide nutrients in a rapid but short-lived manner (Kandel et al., 2020).

The high organic carbon (C) content in Azolla is particularly important for increasing soil organic carbon levels. Research indicates that approximately 90% of Azolla decomposes within four weeks after being incorporated into the soil (Watanabe et al., 1989). As it breaks down, the organic matter undergoes mineralization, during which humic substances are formed. These humic compounds contribute to the accumulation of soil organic carbon, enhancing soil fertility and structure (Bhardwaj & Gaur, 1970).

The continuous use of Azolla as a soil amendment significantly increases soil organic carbon levels. Studies have shown that the inoculation of Azolla leads to a substantial buildup of soil organic carbon, promoting better soil health and nutrient retention (Setiawati et al., 2018). When Azolla is applied in combination with cow manure in equal proportions, the soil organic carbon content increases in the range of 1.3% to 1.7%, demonstrating its effectiveness in improving soil quality (Setiawati et al., 2018). Similarly, Azolla-treated soil has been reported to show a 25.51% increase in oxidizable organic carbon, further emphasizing its positive impact on soil organic matter enrichment (Halder & Kheroar, 2013).

Another significant benefit of Azolla application is its ability to enhance soil microbial activity. The incorporation of Azolla into the soil fosters the growth of beneficial microbial populations, including bacteria, fungi, and actinomycetes. These microorganisms play a vital role in decomposing organic matter, cycling essential nutrients, and improving soil aeration. Moreover, Azolla-enriched soils exhibit increased enzyme activity, which facilitates nutrient recycling and promotes soil fertility (Krishnakumar et al., 2005).

Overall, Azolla acts as a sustainable soil amendment that not only increases soil organic matter but also supports microbial biodiversity, enhances nutrient cycling, and improves soil structure. Its long-term benefits make it a valuable addition to organic farming and environmentally friendly agricultural practices.

Biological Nitrogen Fixation by Azolla

The incorporation of Azolla into rice paddy fields plays a crucial role in enhancing soil fertility and improving the nitrogen content of the soil. This remarkable ability is attributed to the presence of its symbiotic cyanobacterium, Anabaena azollae, which resides within the dorsal leaf cavities of Azolla fronds (Peters & Meeks, 1989). This symbiotic relationship is highly efficient, as Anabaena is capable of fulfilling the entire nitrogen requirement of the host plant through biological nitrogen fixation.

The process of nitrogen fixation in Azolla is closely linked with its photosynthetic activities. Both the Azolla plant and the Anabaena symbiont engage in the Calvin cycle, where the primary product of photosynthesis is sucrose (Van, 1989). A strong metabolic interaction exists between nitrogen fixation and photosynthesis, as the energy molecules ATP and NADPH required for nitrogen fixation are generated through photosynthetic activity. This interdependent mechanism ensures that nitrogen fixation occurs at an optimal rate, benefiting both the Azolla plant and the surrounding crop.

In terms of field application, the nitrogen-fixing capacity of Azolla is highly efficient. Research has shown that Azolla can fix approximately 1.1 kg of nitrogen per hectare per day under favorable conditions. This nitrogen contribution is sufficient to meet the nitrogen demand of a rice crop within just a few weeks (Lumpkin & Plucknett, 1980). In particular, Azolla pinnata has demonstrated an exceptional nitrogen-fixing ability, fixing 75 mg of nitrogen per gram of dry weight per day. Over the course of a year, A. pinnata can generate a biomass yield of 347 tonnes of fresh weight per hectare, containing approximately 868 kg of nitrogen. This nitrogen content is equivalent to 1900 kg of synthetic urea fertilizer, making Azolla an excellent natural alternative for nitrogen enrichment in rice fields.

Despite its significant potential, there exists considerable variation in nitrogen fixation efficiency among different strains of Azolla (Singh, 1988). Several factors influence the growth and nitrogen-fixing capacity of Azolla, including nutrient availability, environmental conditions, inoculation rates, and the timing of application (Kannaiyan, 1993; Singh & Singh, 1995). Proper management of these factors can maximize the effectiveness of Azolla as a biofertilizer, reducing dependency on synthetic fertilizers while maintaining soil health and crop productivity.

By integrating Azolla into agricultural systems, particularly in rice cultivation, farmers can significantly improve soil fertility through sustainable nitrogen fixation. The use of Azolla not only enhances crop yield but also contributes to long-term environmental sustainability by minimizing the adverse effects of chemical fertilizers.

Role of Azolla in Reclaiming Contaminated Soil

The application of Azolla in rice paddy fields has been widely recognized for its ability to enhance soil fertility and improve overall soil health (Peters & Meeks, 1989). Beyond its role as a biofertilizer, Azolla also plays a crucial function in soil reclamation, particularly in the restoration of contaminated or degraded soils. The inoculation of Azolla into agricultural fields has been reported to significantly improve the biological health of the soil, making it an effective tool for sustainable land management and crop productivity.

To maintain long-term soil fertility and sustain rice yields, it is essential to optimize the use of organic, inorganic, and biological inputs in an integrated manner while considering ecological and soil conditions. Azolla, when incorporated into the soil, decomposes rapidly and efficiently supplies nitrogen to crop plants. In addition to nitrogen, it also contributes substantial amounts of phosphorus, potassium, sulfur, zinc, iron, molybdenum, and other essential micronutrients. This enriches the soil and enhances its fertility, making it suitable for crop cultivation in previously contaminated or nutrient-deficient areas.

Improvement in Soil Mineralization and Microbial Activity

One of the major benefits of Azolla in soil reclamation is its role in increasing microbial activity and promoting organic nitrogen mineralization. In lowland rice cultivation, the conversion of organic nitrogen into ammonia is a critical process for plant nutrient uptake (Sahrawat, 1983). The rate of mineralization largely depends on the carbon-to-nitrogen (C:N) ratio of the organic material. Studies indicate that Azolla species with a low C:N ratio undergo rapid mineralization within just two days, whereas species with a higher C:N ratio take around five days to decompose completely (Wang et al., 1987). Despite the variation in mineralization time, the decomposed organic matter significantly contributes to the growth of microbial populations in the soil.

The decomposition of Azolla also results in the formation of humic substances, which further enhance soil fertility by improving its structure, water-holding capacity, and nutrient retention ability (Bhardwaj & Gaur, 1970). Continuous application of Azolla has been found to increase the organic nitrogen content of the soil significantly, ensuring long-term soil productivity. Additionally, the incorporation of Azolla into soil promotes cellulolytic and urea-hydrolyzing activities, leading to a substantial increase in the population of heterotrophic bacteria (Kannaiyan & Subramani, 1992; Kannaiyan & Kalidurai, 1995). The enhancement of soil microbial diversity is also reflected in the increased activity of key soil enzymes such as urease and phosphatase, which play vital roles in nutrient cycling and soil fertility improvement (Thanikachalam et al., 1984; Thangaraju & Kannaiyan, 1989).

Enhancement of Soil Enzymatic Activities

The combined application of nitrogen-fixing green manures such as Sesbania and Azolla has been shown to significantly enhance the activity of soil enzymes, including dehydrogenase, phosphatase, cellulase, and amylase (Kumar & Kannaiyan, 1992). These enzymes are essential for the breakdown of organic matter, making nutrients more available to plants and improving soil structure. Further studies have demonstrated that Azolla application leads to an increase in microbial populations, including total bacteria, cellulolytic, phosphate-solubilizing, and urea-hydrolyzing bacteria (Gopalaswamy & Kannaiyan, 2000). These beneficial microorganisms play an essential role in nutrient cycling and soil detoxification, thereby improving the fertility and health of degraded or contaminated soils.

Azolla in Organic Farming and Sustainable Soil Reclamation

In organic farming systems, Azolla is considered a valuable component due to its ability to increase bacterial, fungal, and actinomycete populations, as well as enhance urease and dehydrogenase activities (Krishnakumar et al., 2005). The presence of these microbial communities improves soil aeration, water infiltration, and organic matter decomposition, leading to better nutrient availability and plant growth. By integrating Azolla into sustainable agricultural practices, particularly in degraded and contaminated soils, farmers can restore soil fertility, reduce dependence on chemical fertilizers, and promote eco-friendly farming practices. The ability of Azolla to fix atmospheric nitrogen, supply essential nutrients, enhance microbial activity, and support soil enzymatic functions makes it a promising natural solution for soil reclamation and sustainable crop production.

Azolla: A Potential Biofertilizer for Enhancing Rice Productivity

The free-floating aquatic fern **Azolla** has gained recognition as a **natural biofertilizer**, offering a sustainable alternative to chemical fertilizers for improving **rice yield**. Its ability to fix atmospheric **nitrogen (N)** through a symbiotic relationship with cyanobacteria makes it a valuable **N source** in rice cultivation (Wagner, 1997). The incorporation of Azolla into paddy fields can **replace 30-60 kg of nitrogen fertilizers per hectare**, contributing to long-term **soil health and sustainability** (Samal et al., 2020).

Impact of Azolla on Rice Growth and Yield

The application of Azolla has a **positive effect** on plant growth, biological yield, and overall nutrient availability in rice fields (Gupta & Potalia, 1990). Studies have shown that incorporating Azolla into **paddy soil** significantly enhances grain yield, **straw yield, dry matter accumulation, and caryopsis formation** (Anjuli et al., 2004). Azolla application has been reported to **increase paddy yields by 8-14%** (Yao et al., 2018) and, in some cases, yield improvements of up to **13%** have been observed (Watanabe, 1977). Azolla incorporation has been linked to **higher rice yield components** (Kannaiyan & Rejeswari, 1983; Islam et al., 1984). Reports indicate a **14-40% increase in rice grain yield** when Azolla is cultivated as a **dual crop**, while monocropping Azolla in the fallow season has resulted in a **15-20% yield improvement** (Samal et al., 2020). The highest rice grain yield was achieved when **Azolla compost was applied at 5.0% of soil weight**, leading to a **13.8% higher yield compared to non-amended soil** (Razavipour et al., 2018). Similarly, incorporating **8-10 tons of Azolla per hectare** resulted in a **47% increase in grain yield over the control** (Singh, 1977). Dual cropping with **Azolla pinnata** further enhances rice yield by **6-29%** (Moore, 1969; Le Van, 1963). Barthakur & Talukdar (1983) also reported a **36.6-38% increase in rice yield** when Azolla was cultivated alongside rice. Additionally, the use of **blue-green algae (BGA)** in conjunction with Azolla has been shown to **improve grain yield and soil quality in organic Basmati rice production** (Singh et al., 2007; Bhuvaneshwari, 2012).

Azolla in Rice-Wheat Cropping Systems

The potential of Azolla extends beyond rice cultivation. Studies suggest that Azolla can be successfully utilized in **rice-wheat cropping systems** to improve soil fertility and increase crop yield (Ali et al., 1998). As a **green manure**, Azolla has been adopted in several developing countries to **fertilize paddy fields naturally**, with an estimated nitrogen fixation of **40–60 kg N/ha** (Rai et al., 2018). Azolla also synthesizes **plant growth regulators** such as **auxins, indole acetic acid (IAA), and gibberellic acid**, which contribute to enhanced crop development (Mishra & Dash, 2014).

Nitrogen Release and Fertilizer Efficiency

The release of nitrogen from Azolla is **gradual**, ensuring sustained nutrient availability for crops. It has been observed that about **70% of the nitrogen fixed by Azolla** is available to the first rice crop, making it comparable to ammonium sulfate (Saha et al., 1982). However, the nitrogen **mineralization process** is faster in **fresh Azolla** compared to dried Azolla, as decomposition occurs more rapidly at **room temperature** (Singh, 1979). The incorporation of Azolla into the soil not only **enhances nitrogen availability** but also facilitates the **release of other essential nutrients**, further improving soil fertility. Field experiments have reported a **9-38% increase in paddy yield** when Azolla was incorporated as a **green manure** (Singh, 1977). Moreover, by integrating Azolla with **chemical fertilizers**, farmers can **reduce synthetic fertilizer use by up to 50%** without significant yield loss (Francisco et al., 2000).

Effect of Azolla on Weed Suppression in Rice Fields

Weeds are a major constraint in rice cultivation, causing yield losses between 15-20%, with extreme cases reaching up to 50% (Sureshkumar et al., 2016). The presence of Azolla in rice paddies acts as a natural weed suppressant by forming a dense floating cover over the water surface, which significantly reduces light penetration to the soil. This limits weed seed germination and inhibits the growth of competing plant species, leading to a 70% reduction in weed emergence (Biswas et al., 2005).

By restricting sunlight exposure, Azolla effectively suppresses the growth of common aquatic weeds such as Echinochloa crus-galli, Cyperus sp., and Paspalum sp. in flooded rice fields. This minimizes weed competition, allowing rice plants to thrive and improving overall crop productivity. The extent of weed suppression increases as the percentage of Azolla cover and water depth rise, creating unfavorable conditions for weed establishment (Kalyanasundaram et al., 1999). Studies have shown that applying organic manure at 10 t ha^{-1} combined with Azolla at 1 t ha^{-1} resulted in the lowest weed count and the highest weed control efficiency in rice crops. The thick Azolla mat floating on the water surface forms a light-impermeable barrier, preventing sunlight from reaching weed seeds and seedlings, thereby restricting their growth (Gnanavel, 2015). Weed suppression by Azolla is highly effective throughout the rice-growing period. At the flowering stage, weed inhibition ranges from 69-100%, while at the harvest stage, weed suppression remains between 86-95%, depending on the weed species (Janiya & Moody, 1984). This natural weed control method has long been recognized in rice fields, where a dense Azolla layer successfully prevents weed development and reduces reliance on chemical herbicides (Shen et al., 1963).

Additional Uses of Azolla

Beyond its role as a biofertilizer and soil enhancer, **Azolla** has numerous other applications, making it a versatile and valuable biological resource. Its uses extend across **agriculture, aquaculture, medicine, environmental management, and even space research**.

Azolla as Fish Feed and Weed Suppressant

Azolla has been widely used as a **natural feed for fish** due to its high protein content and rapid growth rate (Edwards, 1974). Additionally, its ability to form a **dense floating mat** on water surfaces helps in **controlling weed growth** in aquatic ecosystems. By preventing excessive weed proliferation, Azolla creates a more balanced environment for fish and other aquatic organisms.

Azolla for Mosquito Control

The presence of Azolla in stagnant water bodies has been shown to be effective in **controlling mosquito populations**. When Azolla forms a thick layer on the water surface, it restricts **mosquito breeding** by preventing adult mosquitoes from laying eggs and **blocking larvae from reaching the surface to breathe**. This natural mosquito control method has been studied and documented for decades (Ansari & Sharma, 1991; Benedict, 1923; King et al., 1942; Cohn & Renlund, 1953; Shaver, 1954; Neai, 1965; Burkill, 1966).

Azolla as Livestock and Poultry Feed

Azolla is recognized as an excellent **fodder crop** for livestock and poultry due to its **high protein content, essential amino acids, vitamins, and minerals**. It has been incorporated into the diets of various animals, including: **Pigs, ducks, and chickens**: Farmers have long fed Azolla to poultry and pigs as a **nutrient-rich supplement** that enhances growth and productivity (Chevalier, 1926; Fujiwara et al., 1947; Dao & Tran, 1966; Burkill, 1966; Anonymous, 1975). **Cattle**: Studies have shown that Azolla can be used as a **supplemental feed for cows and buffaloes**, improving milk production and overall health (Le Van & Sobochkin, 1963; Dao & Tran, 1966; Sculthorpe, 1967). **Fish**: Azolla has been used in

aquaculture as a protein-rich feed for fish species, promoting **faster growth rates** and enhancing overall **nutritional value** (Le Van & Sobochkin, 1963; Sculthorpe, 1967).

Azolla for Water Purification

Azolla has also been studied for its ability to **purify water** by absorbing **heavy metals, excess nutrients, and other contaminants** from polluted water bodies (Cohn & Renlund, 1953). This makes it a valuable tool in **wastewater treatment and bioremediation**, particularly in regions struggling with water pollution.

Azolla in Traditional Medicine

In some cultures, Azolla has been used for its medicinal properties. For example: In **New Zealand**, people have chewed Azolla to relieve **sore throats** (Usher, 1974). In **traditional herbal medicine**, Azolla has been used as an **ingredient in cough medicine** (Raja et al., 2012). In certain **African tribes**, Azolla has even been utilized in **soap production** due to its natural properties (Chevalier, 1926) **Azolla in Space Research and Human Nutrition** The nutritional richness of Azolla has gained attention in **space research**, where scientists have explored its potential as a **sustainable food source for astronauts**. Due to its rapid growth, high **protein content**, and ability to fix **atmospheric nitrogen**, Azolla has been considered a **component of space diets** in long-term space missions (Katayama et al., 2008). Its ability to thrive in **controlled environments** makes it an ideal candidate for **closed-loop life-support systems** in space habitats.

Government Policies for Implementing Azolla as a Biofertilizer

Several **Asian governments** have actively promoted the use of **biofertilizers**, including Azolla, to enhance **sustainable agriculture**. These policies aim to **reduce dependency on chemical fertilizers**, improve **soil health**, and support **eco-friendly farming practices**.The **Government of India** has taken significant steps to **encourage the use of biofertilizers** in agriculture (Ghosh, 2004). Many **state-level initiatives** are also supporting farmers in adopting **biofertilizer technologies**. For instance, in **Odisha**, farmers have been **trained in Azolla cultivation** to be used as a natural fertilizer (Mishra & Dash, 2014). Similarly, the **Government of Bangladesh** has introduced policies to support **the production and application of biofertilizers**, along with **ongoing research on Azolla** for wetland rice cultivation, particularly in the **Boro rice ecosystem** (Goswami et al., 2014). In **Nepal**, the **Agricultural Biodiversity Policy (2006)** and its **2014 amendment** have emphasized the importance of **biofertilizer usage** as a means of ensuring **sustainable agricultural practices** (Atreya, 2015). Other **Southeast Asian countries** such as **China, Myanmar, Laos, Thailand, Cambodia, and Vietnam** have also shifted their focus towards **sustainable agriculture** by formulating **policies to promote biofertilizers** (Atieno et al., 2020). The **Thailand Institute of Scientific and Technological Research (TISTR)** has undertaken efforts to **identify, select, and commercialize blue-green algae** as biofertilizers, making them more accessible to farmers (Damrongchai, 2000). In the **Philippines**, government programs have encouraged **the incorporation of Azolla** in rice production as an alternative to **excessive chemical fertilizer usage**, promoting a more **environmentally friendly approach** (Rosegrant et al., 1985).

Conclusion

For **sustainable agricultural intensification**, maintaining **healthy soil** is crucial. Azolla contributes significantly to **soil health improvement** by enhancing the **microbial population**

of nitrogen-fixing bacteria and increasing the **soil fertility index** through the accumulation of **essential soil enzymes**. The **rapid growth rate of Azolla** makes it an **environmentally friendly and cost-effective** solution for wetland development. However, before large-scale adoption, it is essential to **evaluate the economic feasibility** of using Azolla, as its cultivation and application can be **labor-intensive**. This technology is most suitable for regions where **farm labor is affordable and readily available**. Beyond its role as a **biofertilizer and livestock feed**, Azolla—often referred to as **'nature's green gold mine'**—has multiple applications. It serves as a **natural water purifier, medicinal plant, human food source, and even a feedstock for biogas production**. The **Azolla-Anabaena system** is an excellent **biofertilization method** for rice crops and has great potential in **agriculture and allied sectors**. However, **focused research and policy interventions** are required to **maximize its potential**. To ensure **the widespread adoption** of Azolla as a **biofertilizer**, it is essential for **policymakers, scientists, and farmers** to work together. **Collaborative efforts** are needed to overcome the challenges in its large-scale implementation, enabling Azolla to become a **key bioinoculant for sustainable agriculture and rural development**.

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