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Azolla Compost as a Sustainable Organic Fertilizer for Improving Soil Fertility and Crop Productivity

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Abstract

The increasing dependence on chemical fertilizers has contributed substantially to concerns regarding soil degradation, nutrient imbalance, environmental pollution, and the long-term sustainability of agricultural production, the use of locally available organic resources has gained considerable attention as an alternative or complementary approach to conventional fertilization. Azolla, a small floating aquatic fern belonging to the family Salviniaceae, is recognized for its rapid growth, high biomass production, and association with nitrogen-fixing cyanobacteria. These characteristics make Azolla a promising source of organic manure and compost. Azolla compost contains organic matter and essential plant nutrients and can contribute to improved soil structure, nutrient availability, microbial activity, and crop growth. Composting Azolla also provides an effective means of converting its rapidly produced biomass into a more stable organic fertilizer. This review discusses the biological characteristics and nutrient potential of Azolla, methods of Azolla compost production, its influence on soil physical, chemical, and biological properties, and its effects on crop productivity. The potential role of Azolla compost in sustainable agriculture, integrated nutrient management, and circular agricultural systems is also discussed. The available evidence indicates that appropriately prepared Azolla compost can serve as a valuable organic fertilizer, particularly when integrated with other nutrient-management practices. Further research is required to standardize composting methods, determine crop-specific application rates, evaluate long-term soil effects, and assess its economic feasibility under different farming conditions.

Keywords: *Azolla, organic fertilizer, compost, soil fertility, crop productivity, sustainable agriculture, nitrogen fixation, organic matter, integrated nutrient management.*

1. Introduction

Agriculture is increasingly challenged by the need to produce sufficient food while maintaining soil health and reducing environmental impacts. Modern crop production has benefited greatly from the use of synthetic fertilizers; however, continuous and imbalanced application of chemical fertilizers can contribute to declining soil organic matter, nutrient losses, soil acidification or salinization in some situations, and contamination of surrounding water resources. These concerns have encouraged researchers and farmers to explore sustainable sources of plant nutrients capable of improving soil fertility while reducing dependence on external inputs [1]. Organic fertilizers derived from plant residues, animal wastes, composts, green manures, and aquatic biomass can contribute to sustainable nutrient management.

Among these resources, *Azolla* has attracted considerable interest because of its exceptionally rapid growth and biological association with nitrogen-fixing microorganisms. *Azolla* is a free-floating aquatic fern that commonly occurs in freshwater environments. Its symbiotic association with the cyanobacterium *Anabaena azollae* enables the plant to obtain biologically fixed nitrogen, resulting in a relatively high nitrogen content compared with many other plant residues.
Historically, *Azolla* has been used as a green manure, particularly in rice-based agricultural systems. Its biomass can be incorporated directly into soil or converted into compost before application. Composting offers several advantages because it stabilizes organic material, reduces the volume of fresh biomass, and produces a more manageable fertilizer. Depending on the species, cultivation conditions, harvesting stage, and composting method, the nutrient composition of Azolla compost may vary considerably [2].

The use of Azolla compost is relevant not only because of its nutrient content but also because organic amendments can influence several components of soil quality. Addition of organic matter may improve soil aggregation, water-holding capacity, microbial activity, and nutrient cycling. Consequently, Azolla compost may provide benefits that extend beyond the direct supply of nitrogen and other nutrients.

This review summarizes current knowledge regarding the use of Azolla compost as an organic fertilizer, with particular emphasis on its production, nutrient characteristics, effects on soil fertility, influence on crop productivity, limitations, and future prospects in sustainable agriculture.

2. Biological Characteristics of Azolla

Azolla is a small aquatic fern that belongs to the family Salviniaceae. Several species of the genus are distributed in tropical and subtropical regions and are capable of forming dense mats on the surface of stagnant or slow-moving freshwater bodies. The plant consists of small overlapping leaves and a branched stem system containing roots that extend into the water [3]. One of the most important characteristics of Azolla is its symbiotic relationship with the nitrogen-fixing cyanobacterium *Anabaena azollae*. The cyanobacterium inhabits specialized cavities within the Azolla leaves and is capable of fixing atmospheric nitrogen. This biological nitrogen fixation contributes to the nitrogen nutrition of the fern and is one of the principal reasons for its agricultural importance [4]. Azolla also possesses a very high relative growth rate under favorable environmental conditions. Adequate moisture, nutrients, light, temperature, and suitable water chemistry can promote rapid biomass production. This rapid growth makes Azolla an attractive biomass resource for agricultural use. However, it also means that management is necessary when Azolla proliferates excessively in water bodies [5]. The high moisture content of freshly harvested Azolla can make direct transportation and storage difficult. Composting can therefore provide a practical approach for transforming fresh Azolla biomass into a more stable and convenient organic fertilizer.

3. Nutrient Composition and Fertilizer Potential of Azolla

The fertilizer value of Azolla is primarily associated with its nitrogen content, although it may also contain phosphorus, potassium, calcium, magnesium, sulfur, and several micronutrients. The actual concentration of these nutrients depends on species, growing environment, age of the biomass, water quality, nutrient availability, and harvesting conditions [6]. The nitrogen-fixing association of Azolla gives it an important advantage over many non-leguminous plant residues. When Azolla biomass is incorporated into agricultural soil, the organic nitrogen contained in its tissues can undergo microbial decomposition and mineralization, gradually becoming available to plants [7].

Azolla biomass also contains organic carbon and other biologically active compounds that can contribute to soil organic matter. During composting, part of the readily degradable organic material is broken down by microorganisms, while more stable organic fractions are formed. The resulting compost can therefore act as both a nutrient source and an organic soil amendment [8]. However, Azolla should not be regarded as a complete substitute for all mineral fertilizers under every agricultural condition. Nutrient concentrations are variable, and the amount of nutrients supplied through compost depends on application rate and nutrient-release characteristics. Its greatest potential may therefore occur as part of integrated nutrient management rather than as a universal replacement for synthetic fertilizers.

4. Production of Azolla Compost

The production of Azolla compost generally involves harvesting fresh biomass, reducing excess water, mixing the biomass with suitable carbon-rich materials when necessary, maintaining adequate moisture and aeration, and allowing microbial decomposition to proceed [9]. Fresh Azolla has a high moisture content and relatively low structural carbon compared with many dry crop residues. Therefore, combining it with materials such as straw, dry leaves, crop residues, or other carbon-rich organic materials can improve the carbon-to-nitrogen balance and physical structure of the composting mixture.

A general composting process includes the following stages:

1. Collection of Azolla biomass: Fresh, healthy Azolla is harvested from cultivation ponds or suitable freshwater production systems.

2. Removal of excess water: The biomass is drained or partially dried to facilitate handling.

3. Mixing with organic residues: Dry plant residues may be incorporated to improve aeration and balance the composting substrate.

4. Composting: The mixture is maintained under appropriate moisture and aeration conditions.

5. Turning: Periodic turning can improve oxygen supply and promote uniform decomposition.

6. Maturation: Compost is allowed to stabilize until it becomes dark, crumbly, and relatively free from the recognizable characteristics of the original materials.

7. Application: Mature compost is incorporated into soil or applied around crops according to crop requirements.

The quality of the final compost depends strongly on the composition of the starting materials and the conditions maintained during composting. Proper maturation is important because incompletely decomposed organic materials can temporarily immobilize nutrients or create undesirable conditions in the soil.

5. Effect of Azolla Compost on Soil Physical Properties

Soil physical quality is closely associated with organic matter content, aggregation, porosity, water movement, and root development. Continuous cultivation can reduce soil organic matter and adversely affect soil structure, particularly when crop residues are removed and organic inputs are limited.

Azolla compost contributes organic material to the soil and may promote the formation and stabilization of soil aggregates. Improved aggregation can increase pore continuity and improve the balance between water retention and drainage [10]. Organic amendments may also reduce soil compaction and create a more favorable environment for root growth.

The addition of organic matter can increase the soil's capacity to retain water, which may be particularly beneficial in soils with low organic matter. Improved water retention can reduce short-term water stress and increase the efficiency with which crops use available moisture.

The magnitude of these effects depends on soil texture, climate, compost characteristics, application rate, and duration of use. Therefore, long-term field experiments are necessary to establish how repeated Azolla compost application influences soil physical properties under different farming systems.

6. Effect on Soil Chemical Properties

Organic amendments can influence several important chemical characteristics of agricultural soils. Azolla compost may contribute to the gradual improvement of soil organic carbon and nutrient availability.

6.1 Nitrogen Availability

Nitrogen is one of the most important nutrients supplied by Azolla-derived organic material. During decomposition, organic nitrogen is converted through microbial processes into mineral forms that can become available for plant uptake.

Unlike highly soluble mineral nitrogen fertilizers, organic nitrogen generally undergoes gradual mineralization. This may reduce the risk of rapid nutrient losses under suitable conditions, although nitrogen losses can still occur through volatilization, leaching, or denitrification depending on soil and environmental conditions.

6.2 Phosphorus and Potassium

Azolla compost can also supply phosphorus and potassium. Although the quantities may not always meet the complete nutritional requirements of high-yielding crops, their contribution can complement other nutrient sources.

Organic matter may additionally influence phosphorus availability by modifying microbial activity and chemical interactions within the soil.

6.3 Soil Organic Carbon

One of the major advantages of organic fertilizers is their contribution to soil organic matter. Increasing soil organic carbon can improve nutrient retention and provide energy for soil microorganisms. Repeated organic amendment application may therefore contribute to the gradual development of healthier and more biologically active soils.

6.4 Soil Reaction and Nutrient Retention

Depending on its chemical composition and the characteristics of the receiving soil, compost may influence soil pH and nutrient retention. Organic matter contains functional groups capable of interacting with mineral nutrients, potentially increasing nutrient retention and reducing losses.

7. Influence on Soil Biological Activity

Soil is a biologically active ecosystem containing bacteria, fungi, actinomycetes, nematodes, and numerous other organisms. Organic amendments provide carbon substrates that can stimulate microbial activity and nutrient cycling [11]. Azolla compost can serve as a source of readily and slowly decomposable organic compounds. As microorganisms decompose these materials, nutrients are released and transformed into forms that may become available to crops.

Enhanced microbial activity may also contribute to the formation of soil aggregates and the decomposition of crop residues. In addition, organic amendments can influence the abundance and activity of beneficial microorganisms involved in nutrient cycling [12]. The biological effects of Azolla compost are influenced by compost maturity, application rate, soil conditions, temperature, moisture, and existing microbial communities. More research is needed to understand the long-term effects of repeated Azolla compost application on soil microbial diversity and functional processes.

8. Effect of Azolla Compost on Crop Growth

Improved nutrient availability, soil structure, water retention, and biological activity can collectively influence crop growth. Application of Azolla-derived organic fertilizer has been associated in various studies with improvements in plant height, leaf development, root growth, biomass accumulation, and other growth characteristics [13]. The response of a crop depends on the amount of compost applied and its nutrient composition. Crops with high nitrogen demand may respond particularly well where Azolla compost supplies a substantial amount of available nitrogen. However, the nutrient-release rate of compost differs from that of soluble mineral fertilizers. Azolla compost may also have indirect effects on crop growth by improving the physical environment surrounding plant roots. Better soil aggregation and moisture retention can promote root development and improve nutrient uptake.

9. Effect on Crop Yield and Productivity

The ultimate objective of fertilizer application is to improve crop productivity while maintaining soil quality. Azolla-based organic amendments have demonstrated potential for increasing yields in several agricultural systems, particularly when used in combination with other nutrient sources.

In rice cultivation, Azolla has historically been used as a green manure because of its nitrogen-fixing capability. Its use can contribute to nitrogen supply and improved crop performance. Similar principles may apply to other crops when appropriately processed Azolla compost is incorporated into the soil.

The effectiveness of Azolla compost can be influenced by crop species, soil fertility, environmental conditions, application timing, compost maturity, and interactions with mineral fertilizers. In nutrient-deficient soils, combining organic and inorganic fertilizers may provide both immediately available nutrients and longer-term soil-improvement benefits [14]. Therefore, integrated nutrient management strategies involving Azolla compost may provide a more reliable approach than relying exclusively on Azolla-derived fertilizer.

10. Azolla Compost in Integrated Nutrient Management

Integrated nutrient management aims to maintain crop productivity through the balanced use of organic, inorganic, and biological nutrient sources. Azolla compost can contribute to this approach by providing organic matter and nutrients while potentially improving nutrient-use efficiency [15]. A combination of Azolla compost and mineral fertilizers may be particularly useful. Mineral fertilizers can supply nutrients in readily available forms during periods of high crop demand, whereas organic amendments contribute to soil organic matter and gradual nutrient release. Such integration may reduce the quantity of mineral fertilizer required in some production systems, although the exact reduction should be determined through crop- and soil-specific experiments rather than assumed universally. Integrated use can also improve the sustainability of nutrient management by recycling locally available biomass and reducing dependence on externally purchased inputs.

11. Environmental Benefits

The use of Azolla compost has potential environmental benefits when the biomass is produced and managed appropriately.

11.1 Recycling of Biomass

Azolla can be converted from rapidly growing aquatic biomass into a useful agricultural input. Composting provides a pathway for nutrient recycling and reduces the need to dispose of excess biomass.

11.2 Reduction in Synthetic Fertilizer Dependence

Where Azolla compost supplies a meaningful proportion of crop nutrient requirements, it may reduce dependence on synthetic fertilizers. This can contribute to more diversified nutrient-management systems.

11.3 Improvement of Soil Health

Organic amendments can support soil organic matter and biological activity, contributing to long-term soil health.

11.4 Contribution to Circular Agriculture

Azolla compost fits within circular agriculture because nutrients and biomass are recycled rather than treated solely as waste. Production systems can potentially link Azolla cultivation, compost production, and crop production into a resource-recycling cycle.

12. Limitations and Challenges

Despite its potential, several limitations need to be considered before widespread adoption of Azolla compost. First, the nutrient composition of Azolla can vary substantially depending on growing conditions. Consequently, fertilizer recommendations based on generalized nutrient values may not be sufficiently accurate. Second, fresh Azolla contains a high proportion of water, making transportation and storage expensive. On-farm composting or production near the point of application may therefore be more practical. Third, composting requires appropriate management of moisture, aeration, temperature, and carbon-to-nitrogen balance. Poorly managed compost may mature slowly or produce an unstable product. Fourth, Azolla biomass harvested from contaminated water bodies may accumulate undesirable substances. Therefore, biomass intended for agricultural use should preferably be produced in controlled, clean environments or tested for relevant contaminants. Finally, large-scale production requires appropriate infrastructure, labor, water resources, and economic assessment. The environmental and economic benefits may differ among farming regions.

13. Economic Potential

The economic feasibility of Azolla compost depends largely on the availability of biomass and the cost of production. When Azolla can be cultivated using locally available resources, the cost of producing organic fertilizer may be lower than purchasing commercial organic amendments. Small and marginal farmers may particularly benefit from on-farm Azolla production because the biomass can be generated locally and incorporated into nutrient-management practices. However, labor requirements for harvesting, draining, composting, and application must be included in economic calculations. Future studies should compare the production cost of Azolla compost with other organic fertilizers and mineral fertilizers under different cropping systems.

Such assessments should include not only fertilizer costs but also changes in crop yield, soil fertility, water use, labor, and long-term soil productivity.

14. Future Prospects

Research on Azolla compost should move beyond short-term yield experiments and investigate its long-term effects on soil health and agricultural sustainability. Several areas deserve particular attention.

First, standardized methods for Azolla compost production should be developed to ensure consistent nutrient quality. Second, crop-specific application rates should be established through replicated field experiments. Third, studies should examine the effects of repeated applications over multiple cropping seasons. The interaction between Azolla compost and beneficial soil microorganisms also represents an important research area. Advances in soil microbiology and molecular techniques could help identify changes in microbial communities associated with repeated Azolla amendment.

There is also potential for integrating Azolla compost with precision agriculture. Soil testing, crop nutrient monitoring, and site-specific fertilizer recommendations could improve the efficiency of Azolla-derived nutrient inputs. Finally, life-cycle assessment and economic analysis are required to determine the overall environmental and financial sustainability of Azolla-based fertilizer systems.

15. Conclusion

Azolla compost represents a promising organic fertilizer resource for sustainable agricultural production. Its value is associated with the rapid biomass production of Azolla, its nitrogen-fixing association with cyanobacteria, and its capacity to provide organic matter and nutrients to agricultural soils. Properly prepared Azolla compost can contribute to improved soil structure, nutrient availability, microbial activity, and crop growth. Its greatest potential may be realized when incorporated into integrated nutrient-management systems alongside appropriate mineral and biological inputs.

However, the performance of Azolla compost is not uniform and depends on biomass quality, composting conditions, application rate, soil characteristics, crop requirements, and environmental conditions. Consequently, standardized production and field-based nutrient recommendations are essential.

Overall, Azolla compost should be considered a valuable component of sustainable soil-fertility management rather than a universal replacement for synthetic fertilizers. Its use can support nutrient recycling, improve soil quality, and contribute to circular agricultural systems. Continued multidisciplinary research combining agronomy, soil science, microbiology, environmental science, and agricultural economics will be important for developing efficient and economically viable Azolla-based fertilizer technologies.

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