

## ***Azolla* as a Source of Biofertilizer for Sustainable Crop Production – A Literature Review**

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**Abstract** - *Azolla* has been exploited widely as biofertilizer for rice and some crop plants, and it fixes atmospheric nitrogen due to the presence of a symbiotic cyanobacterium, *Anabaena azollae*. It has several other uses such as food, feed, biogas producer and hyper accumulator of heavy metals, etc. Agricultural fertilizers are essential to enhance proper growth and crop yield. Recently, farmers have been using chemical fertilizers for quicker and better yield. But these fertilizers endanger ecosystems, soil, plants, and human and animal lives. The use of bio-fertilizers like *Azolla* not only increases the crop productivity but also improves the long term soil fertility. This multidimensional uses of *Azolla-Anabaena* system would be ideal and environment friendly in sustainable agriculture. The current study critically reviewed the *Azolla*'s potential capacity to be used in sustainable agriculture.

**Keywords:** *Azolla*, Sustainable Agriculture, Biofertilizer, Nitrogen

### **INTRODUCTION**

Chemical fertilizers have been widely used to achieve maximum productivity in conventional agricultural systems. The continuous and excessive utilization of chemical fertilizers plays a major role, directly and/or indirectly, in changing environmental conditions (Ali *et al.*, 2021). To overcome this problem and achieve food security for the rising population, a new sustainable approach is needed for agriculture (Glick, 2018). This has made the environmentalists to switch over to organic farming. Organic farming has emerged as an important priority area globally in view of the growing demand for safe and healthy food and long term sustainability and concerns on environmental pollution associated with the indiscriminate use of agrochemicals. Organic farming not only ensures food safety but also improves the biodiversity of soil (Megali *et al.*, 2014).

Biofertilizers are an important component of organic farming, which contains live microorganisms in carrier-based formulations that can be applied directly in the soil, seed, or

seedling stage. On application, it improves the nutrient status of the plant by efficient nitrogen fixation or phosphate solubilization or by increasing the number of microorganisms that assist in the availability of nutrients which are easily assimilated by the plants. Biological control of various phytopathogens is also another facet of using biofertilizers in agriculture (Singh *et al.*, 2021; Santhiya and Jeeva, 2022).

The aquatic fern *Azolla* is an excellent biofertilizer and green manure having global distribution. Ability of *Azolla*-*Anabaena* system to fix atmospheric nitrogen at faster rates makes it an outstanding agronomic choice for the cultivation of rice under tropical conditions (Yadav *et al.*, 2014). It has the property to multiply faster at very high rates and covers the surface of water bodies; thus, it forms a thick mat and helps in reducing the volatility of ammonia in the fields. *Azolla* can be used as a biofertilizer in various crops such as rice, wheat, taro, banana and tomatoes (York and Garden, 2016). It is an environmentally safe, non-toxic and preferable fertilizer resource for household gardening and organic farming (Indraniet *et al.*, 2019). The application of *Azolla* as a biofertilizer provides natural source nutrients and has tremendous potential to improve soil health and boost yield sustainability (Pereira, 2017; Akhtar *et al.*, 2020). It can be an alternative to improve rice yield without degrading the environment. It provides a natural source of many nutrients, especially N, improves the availability of other nutrients, plays a critical role in weed suppression, enhances soil organic matter, and improves efficiency of the inorganic fertilizers while maintaining the suitable soil pH condition (Thapa and Poudel, 2021).

Sustainable development refers to a mode of human development in which resource use aims to meet human needs while preserving the environment so that these needs can be met for both present and future generations (Mishra and Dash, 2014). *Azolla* is one of the hyperaccumulator plants which can absorb heavy metals 50–500 times faster than conventional plants; it has significantly helped the revolutionary progress of the phytoextraction technique (Subedi and Shrestha, 2015). This aquatic fern is used as a basis of green manure and decomposed organic material (Razavipou *et al.*, 2018). Since *Azolla* has various contributions in increasing crop yield without degrading the environment.

### *Azolla*

*Azolla* sp. is a tiny free-floating fresh water fern (Plate 1) of tropical and sub-tropical Asia, Africa and America (Mishra and Dash, 2014). The name *Azolla* is derived from Greek word *azo* (to dry) and *allyo* (to kill) meaning that plant dies when it dries (Svenson, 1944).

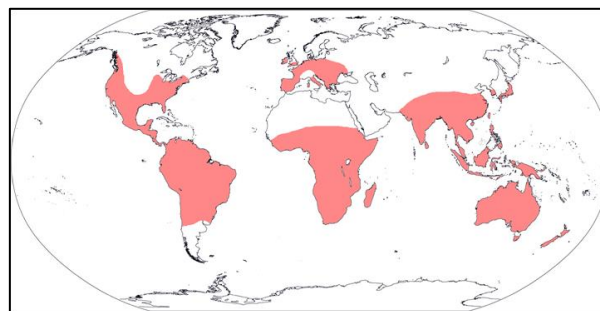


**Plate 1. A) *Azolla* sp. habit; B) surface of the paddy field covered by *Azolla* sp.; C) *Azolla* species associated with wetland plants**

The Genus *Azolla* was established by Lamarck in the year 1783 and placed it in the family Salviniaceae under the order Salviniiales. However, *Azolla* is placed in the monotypic family Azollaceae and there are seven extant Species of *Azolla* (Hills and Gopal, 1967; Konar and Kapoor, 1972). *Azolla* is categorized into two Sub-Genus viz. *Euazolla* and *Rhizosperma* (Svenson, 1944). There are now seven extant species of the family Salviniaceae – *Azolla caroliniana* Willd., *Azolla cristata* Kaulf., *Azolla filiculoides* Lam., *Azolla imbricata* (Roxb. ex Griff.) Nakai, *Azolla mexicana* C. Presl, *Azolla microphylla* Kaulf. and *Azolla pinnata* R. Br (IPNI version 1.1). The Sub-Genus *Euazolla* is characterized by the presence of three floats of megasporocarps and In contrast, the Sub-Genus *Rhizosperma* consists of nine megaspore floats. The trichomes are important in the identification of the organism at the Species level (Lumpkin and Plucknett, 1982; Nayak and Singh, 1988).

### Distribution

*Azolla* occurs naturally in freshwater ditches, ponds, lakes and sluggish rivers of warm-temperate and tropical regions (Fig. 1). Its absence from regions that have prolonged freezing or aridity (Small and Darbyshire's, 2011).



**Fig. 1. Distribution map of *Azolla* (Source:Small and Darbyshire's, 2011).**

### Habit and Morphology

The *Azolla* plants are delicate, small and triangular or polygonal in shape. It is free floating and aquatic but can grow on moist soils as long as the moisture persists in the soil. The sporophytic plant has a horizontal rhizome of 0.5 to 7 cm in diameter with branches having densely arranged and overlapping leaves. A leaf consists of a thick dorsal lobe and a thin ventral lobe. The symbiotic Blue Green Alga is confined to the dorsal lobe (Peters and Mayne, 1974).

An epidermis covers the surface of the dorsal lobe and the epidermis has vertical rows of single celled stomata and trichomes of one or more cells. The ventral lobe which helps in floating due to its convex surface touching water has a few stomata and trichomes (Eames, 1936). Its ventral surface has a multi-branched rhizome that bears small leaves. It contains hanging roots into water to absorb the nutrient contents directly (Roger, 1999). The leaves

consist of chlorophylls and a colorless lobe to supply buoyancy. Each lobe contains a cavity that provides a microcosm environment with self-developed and defined. It behaves as a symbiotic unit association when an energetic and metabolic reaction occurs (Adhikari *et al.*, 2020).

### **Azolla as Green manure**

*Azolla* was primarily grown as a green manure for rice, but it is also grown with water bamboo (*Zizania aquatica*), arrowhead (*Sagittaria sagittifolia*) and taro (*Colocasia esculenta*) (Anonymous, 1975). The positive effect was recorded with *Azolla* green manure on the number of shoots, length of longest leaf, fresh weight, and dry weight of rice plants (Ngo, 1973). The *Azolla* cultivation increased the nitrogen content of the soil to a level equal to that produced by a crop of soybeans (Shen *et al.*, 1963). *A. filiculoides* could provide one half of the nitrogen requirement for rice if it were grown as a green manure before rice seeding (Taller *et al.*, 1977). Two successive *Azolla* layers, incorporated into the soil before rice transplanting, can supply 50 percent of the nitrogen necessary to produce 5 tons of rice per hectare (Tran and Dao, 1973).

The application of *Azolla* as green manure, it can be collected directly from ponds/ditches. It may be grown in nurseries as specified earlier and can also be applied in the field. A thick mat of *Azolla* will be formed after application in about 2-3 week time and can be incorporated in the soil. Rice can also be transplanted in the field subsequently. Single super phosphate (25-50 kg ha<sup>-1</sup>) is applied in split doses. After analyzing the soil P-status the dosage of the same can be reduced. Cattle dung or slurry may also be used instead of single super phosphate. In case of pest infestation or attack, pest control measures have to be undertaken. *Azolla* application by this mode contributes around 20-40 kg N ha<sup>-1</sup> (Yadav *et al.*, 2014). Fresh *Azolla* into the soil significantly increased water holding capacity, organic carbon, ammonium nitrogen, nitrate-nitrogen and its available phosphorus, potassium, calcium and magnesium, while it decreased pH and bulk density, such incorporation significantly raised the yield of mung beans (Raja *et al.*, 2012).

In dual cropping, *Azolla* is grown along with rice and each crop of *Azolla* contributes on an average 30 kg N ha<sup>-1</sup>. After 7-10 days of transplantation fresh inoculums of *Azolla* is applied in the field at the rate of 0.50-1.0 ton ha<sup>-1</sup>. Single super phosphate is applied at the rate of 20 kg ha<sup>-1</sup> in split doses. In about 15-20 days time a thick mat of *Azolla* is formed. *Azolla* thus incorporated decomposes in about 8-10 days time and release the fixed nitrogen. Another crop of *Azolla* can be raised in a similar way during the crop cycle of rice. *Azolla* production technology is simple and not very expensive and at the same time it is very efficient in terms biomass accumulation and nitrogen fixation. The rice growing season is also conducive for the growth of *Azolla* plants. The dual application does not have any negative influence on the rice crop (Yadav *et al.*, 2014).

### ***Azolla* - Soil nutrient availability**

*Azolla* has a remarkable ability to accumulate K in its tissues in a low K environment; it decomposes rapidly and releases nutrients N, P and K into the field after field water is drained (Bhuvaneshwari and Singh, 2015). It solubilizes Zinc (Zn), Iron (Fe), and Magnesium (Mg), making them available to the rice crop, and releases plant growth regulators and vitamins that promote the crops to grow faster (Bhusal and Thakur, 2021). Its continuous application increased the soil nutrient availability (Subedi and Shrestha, 2015). In general, the use of *Azolla* improves soil nutrient availability through biological activity, which also helps to build up the micro flora for mineralization. When *Azolla* decayed, it released soil-available P into the soil (Watanabe *et al.*, 1989). There was no significant difference at the beginning of available soil P in *Azolla* added paddy soils (Rivai *et al.*, 2013). However, there was an 89% increase in *Azolla* added available soil P at rice panicle initiation. Similarly, found that P and Ca contents were also higher in *Azolla*, averaging 124.83 ppm and 345.3 mg/100g (Halder and Kheroar, 2013). *Azolla* treated soil showed a 29.12 % increase of K (Dey *et al.*, 2018). The *Azolla* show the positive results of integrated soil nutrient management practices, which are lacking in many Asian countries.

*Azolla* helps in addition of organic matter and release of cations such as Magnesium, Calcium and Sodium. The total N, available P and exchangeable K in the soil and N-uptake by rice can be improved (Subedi and Shrestha, 2015). Application of *Azolla* also plays a definite role in enhancing soil fertility by increasing available nitrogen, organic carbon, phosphorous and potassium (Mandal *et al.*, 1999). Their utilization also helps curb NH<sub>3</sub> volatilization, prevent rise in pH, reduce water temperature, build up organic matter, and influence the transformation and availability of iron, manganese, zinc, and copper, which improves the infiltration and movement of water in soil (Mandal *et al.*, 1999, Pabby *et al.*, 2004). Therefore, *Azolla* application is considered as a good practice for sustaining soil fertility and crop productivity irrespective of some limitations (Subedi and Shrestha, 2015).

### **Effect of *Azolla* on soil organic matter**

*Azolla* compost impact plant growth and yield positively and improve the organic matter in the soil (Gupta and Potalia, 1990). It maintains its reserve for a long time by releasing its content materials slowly, which provides advantages over raw, unrotted organic matter and chemical fertilizers (Kandel *et al.*, 2020). The high organic C content of *Azolla* contributes to the increase in organic Carbon. According to 90% of *Azolla* was degraded in 4 weeks (Watanabe *et al.*, 1989). The *Azolla* that had been absorbed into the soil would shortly be mineralized. It would generate humic substances as a result of the mineralization process which would also yield soil organic C (Bhardwaj and Gaur, 1970). The inoculation of *Azolla* built up a considerable soil organic carbon content (Setiawati *et al.*, 2018). *Azolla* and cow manure equal combination increased the soil organic C content ranging from 1.3– 1.7 % (Setiawati *et al.*, 2018). Similarly, it was reported that *Azolla* treated soil oxidizable organic C increased 25.51% (Halder and Kheroar, 2013). The higher soil microbial populations of bacteria, fungi, actinomycetes, and higher enzyme activities in *Azolla* incorporated soil, increasing nutrient recycling in the soil (Krishnakumar *et al.*, 2005).

### Biological nitrogen fixation

Application of *Azolla* in rice paddy fields has a positive role in improving the soil fertility index. The ability to fix nitrogen is due to the presence of the symbiotic cyanobacterium *Anabaena* that occurs in the dorsal leaf cavities of the fronds (Peters and Meeks, 1989). The symbiont is able to meet the entire nitrogen requirement of the association. The Calvin cycle operates in both the partners and the primary end product of photosynthesis is sucrose (Van, 1989). A strong interaction exists between nitrogen fixation and photosynthesis and the source of ATP and NADPH is photosynthesis. The capacity of *Azolla* to fix nitrogen in the field has been estimated at  $1.1 \text{ kg N ha}^{-1} \text{ day}^{-1}$  and this fixed nitrogen is sufficient to meet the entire nitrogen requirement of the rice crop within a few weeks (Lumpkin and Plucknett, 1980). *A. pinnata* fixes  $75 \text{ mg N g}^{-1} \text{ dry weight day}^{-1}$  and produces a biomass of 347 tonnes fresh weight  $\text{ha}^{-1}$  in a year. This biomass contains 868 kg of nitrogen, which is equivalent to 1900 kg of urea. A wide variability regarding growth and nitrogen fixation among different strains of *Azolla* is observed (Singh, 1988). Among the several factors that influence the growth and nitrogen fixing potential of *Azolla* are nutrient availability, rate, and the time of inoculation, etc. (Kannaiyan, 1993; Singh and Singh, 1995).

### Role of *Azolla* in reclamation of contaminated soil

Application of *Azolla* in rice paddy fields has a positive role in improving the soil fertility index (Peters and Meeks, 1989). To sustaining rice yields, inoculation of *Azolla* has been reported to enhance the soil biological health. It is important to optimize use of organic, inorganic and biological inputs in an integrated manner taking into consideration the ecological and soil conditions to sustain crop productivity. *Azolla* decomposes rapidly in soil and supply nitrogen to the crop plants. It contributes significant amounts of phosphorus, potassium, sulfur, zinc, iron and molybdenum in addition to other micronutrients besides addition of nitrogen. The biological health of the soil due to application of *Azolla* has resulted in improving mineralization and consequent increase in the microbial status of the soil. In low land rice cultivation mineralization of organic nitrogen to ammonia is an important process (Sahrawat, 1983).

The rate of mineralization is influenced by factors such as C: N. *Azolla* species with a low C: N mineralized in 2 days while the species with high C:N mineralized in 5 days (Wang *et al.*, 1987). The decomposed organic matter plays an active role in the development of microbial population irrespective of the time taken for mineralization. Soil fertility is also influenced by the humic substances formed during the decomposition of *Azolla* (Bhardwaj and Gaur, 1970). The continuous application increased the organic nitrogen content of the soil significantly. Increased cellulolytic and urea hydrolyzing activities in addition to significant increase in the population of heterotrophic bacteria (Kannaiyan and Subramani, 1992; Kannaiyan and Kalidurai, 1995) and increased soil urease and phosphatase activity (Thanikachalam *et al.*, 1984; Thangaraju and Kannaiyan, 1989). Combined incorporation of nitrogen fixing green manures such as *Sesbania* and *Azolla* shows significant enhancement in the activity of soil enzymes such as dehydrogenase, phosphatase, cellulose and amylase

(Kumar and Kannaiyan, 1992). Similar enhancement in the microbial population, total bacterial, cellulolytic, phosphate solubilising and urea hydrolysing bacteria was observed (Gopalaswamy and Kannaiyan, 2000). Maximum population of bacteria, fungi and actinomycetes and high urease and dehydrogenase activities due to organic farming using *Azolla* as one of the components (Krishnakumar *et al.*, 2005).

### ***Azolla*: potential biofertilizer for increasing rice productivity**

The application of free-floating aquatic fern *Azolla* as a biofertilizer can be an alternative to improve rice yield without degrading the environment (Plate 1) (Thapa and Poudel, 2021). *Azolla*, offers significant potential as an N source in rice production (Wagner, 1997). Farmers can manage around 30-60 kg by incorporating *Azolla* at the rate of 16000 kg ha<sup>-1</sup> in rice crops instead of supplying through N fertilizers, given the sustainability of soil health (Samal *et al.*, 2020). *Azolla* application desirably affects plant growth, biological yield and enhancing nutrient quality (Gupta and Potalia, 1990). *Azolla* incorporation in paddy fields increased grain yield, straw yield, caryopsis, and dry matter (Anjuli *et al.*, 2004). Its incorporation increases the paddy yield by 8-14% (Yao *et al.*, 2018). The rice yield increases up to 13% when *Azolla* was used as a biofertilizer in rice crops (Watanabe, 1977). *Azolla* application increased the yield components of rice (Kannaiyan and Rejeswari, 1983; Islam *et al.*, 1984). An increase in grain yields of rice from 14 - 40% has been reported, with *Azolla* being used as a dual crop and by 15-20 % being monocropping during the fallow season (Samalet *et al.*, 2020). The highest rice grain yield when the application of *Azolla* compost at 5.0% of soil weight, which was on average 13.8% higher than that of the non-amended control (Razavipour *et al.*, 2018). The incorporation of 8-10 t of *Azolla* ha<sup>-1</sup> produced the exact rice yield, 47% increase in grain yield over control (Singh, 1977). The rice yield can be increased by 36.6 -38% by using *Azolla* as a dual crop (Barthakur and Talukdar, 1983). *Azolla* dual cropping increases rice yield by 14-40% and 6-29% higher grain yield by growing *A. pinata* as a dual crop with rice (Moore, 1969; Le Van, 1963). Utilization of blue green algae increase yield in organic Basmati rice and improvement in grain and soil quality (Singh *et al.*, 2007; Bhuvaneshwari, 2012). These findings showed that the application of *Azolla* as a biofertilizer has positive and significant improvement in the rice yield.

The *Azolla* can successfully be used for increasing crop yield in a rice-wheat cropping system (Ali *et al.*, 1998). *Azolla* has been considered green manures in several developing countries to fertilize the paddies and improve the yields, which fixes nearly 40–60 Kg N/ha of rice crop (Rai *et al.*, 2018). They are phototrophic in nature and produce auxin, indole acetic acid and gibberillic acid, and fix 20-30 kg nitrogen/ha in submerged rice fields. As they are abundant in paddies, they are also referred as ‘paddy organisms’ (Mishra and Dash, 2014). The release of N by *Azolla* is slow and its availability to the first crop of rice is about 70% to that of ammonium sulphate. Moreover, the release of nitrogen is faster as compared to nitrogen fixing cyanobacteria (Saha *et al.*, 1982). Fresh *Azolla* releases its N faster as compared to dried *Azolla* due to rapid mineralization and mineralization of N is faster at room temperatures (Singh, 1979). The utilization of *Azolla* as green manure has been extensively investigated and an increase in paddy yield ranging from 9-38% has been

observed in field experiments when *Azolla* was incorporated to the soil (Singh, 1977). Incorporation of *Azolla* into the soil also enhances the release of other nutrients. A 50% reduction in chemical fertilizer use can be achieved without significant loss to the rice yield with the use of *Azolla* along with chemical fertilizer (Francisco *et al.*, 2000).

### Effect of *Azolla* in weeds

Weeds reduce the Rice yield ranging from 15 – 20% and up to 50% (Sureshkumar *et al.*, 2016). *Azolla* covering water surface reduces light penetration of soil surface, resulting in the depreciation in the germination of weeds (70% of the weed). Thus, the growth of *Azolla* reduces aquatic weeds in flooded rice fields like *Echinochloa crus-galli*, *Cyperus* sp., *Paspalum* sp. and so on and, this leads to improve crop growth and productivity (Biswas *et al.*, 2005). The degree of suppression increases with an increase in the percent of *Azolla* cover and water depth (Kalyanasundaram *et al.*, 1999). Application of presumed at 10 t ha<sup>-1</sup> + *Azolla* at 1 t ha<sup>-1</sup> recorded the least weed count and highest weed control index in rice crop, as the thallus growth formed a very thick mat on the surface of the water, shortening the interception of light by weed seeds and seedlings (Gnanavel, 2015). Weeds were suppressed by 69 – 100% at rice flowering and 86 – 95 % at harvest depending upon weed species due to the use of the *Azolla* (Janiya and Moody, 1984). The ability of a thick, light-proof *Azolla* mat to suppress weed development has long been observed in rice field (Shen *et al.*, 1963).

### Other uses

*Azolla* used as fishfood and weed control (Edwards, 1974); Mosquito control (Ansari and Sharma, 1991; Benedict, 1923; King *et al.*, 1942; Cohn and Renlund, 1953; Shaver, 1954; Neai, 1965; Burkill, 1966); A fodder crop (Dao, 1973). *Azolla* was fed to pigs, ducks and chickens (Chevalier, 1926; Chevalier, 1926; Fujiwara *et al.*, 1947; Dao and Tran, 1966; Burkill, 1966; Anonymous, 1975); cattle (Le Van and Sobochkin, 1963; Dao and Tran, 1966; Sculthorpe, 1967); fish (Le Van and Sobochkin, 1963; Sculthorpe, 1967). *Azolla* has been found to help purify water (Cohn and Renlund, 1953) and to be an ingredient in soap production by some African tribes (Chevalier, 1926). It was chewed to cure sore throat in New Zealand (Usher, 1974). *Azolla* is used for preparing cough medicine (Raja *et al.*, 2012). *Azolla* as a component of Space Diet (Katayama *et al.*, 2008) and also used in the production of biogas (Das *et al.*, 1994).

### Government Policies to implement *Azolla* as biofertilizers

Many Governments of Asian countries have implemented policies which have directly and indirectly supported in the biofertilizers implementation. The Government of India has been encouraging the use of biofertilizers in agriculture (Ghosh, 2004). State level governments are also emphasizing the biofertilizers usages. The government of Odisha, has trained farmers to utilize *Azolla* as a biofertilizers (Mishra and Dash, 2014). The government of Bangladesh has put forward the policies to support the production and implementation of bio-fertilizers. It has also supported the ongoing research on *Azolla* for wetland Boro rice (Goswami *et al.*, 2014). Similarly, Nepal's Agricultural Biodiversity Policy, 2006 has emphasized on use of biofertilizers Amendment in 2014 (Atreya, 2015). Countries; China,



Myanmar, Lao PDR, Thailand, Cambodia and Vietnam government have shifted their focus in promoting sustainable agriculture, thus emphasizing the policies in biofertilizers promotion (Atieno *et al.*, 2020). Thailand Institute of Scientific and Technological Research (TISTR) have selected and commercialized blue-green algae for use as biofertilizers (Damrongchai, 2000). Philippines government has developed program to promote the use of *Azolla* incorporation instead of heavy incorporation of chemical fertilizer during rice production (Rosegrant *et al.*, 1985).

## Conclusion

The fundamental to sustainable intensification of agriculture is effective soil health management and *Azolla* has been known to influence the dynamics of the total soil and microbial population of nitrogen fixing bacteria. The soil fertility index will improve due to the accumulation soil enzymes. Therefore, we need to have efficient strains of *Azolla* to maintain the soil fertility. The high growth rates of *Azolla* reduce the environmental risks, and it is a cost-effective method for developing wetlands. However, before using *Azolla*, the economics of using *Azolla* should be considered because technology is very labor-intensive, and it is suitable for adoption in locations where farm labor is affordable. Besides its utilization as biofertilizer and livestock feed, *Azolla*, the ‘green gold mine’ of the nature is also used as medicine, water purifier, human food and for production of biogas. The *Azolla-Anabaena* system is an excellent biofertilizer for rice crop and it also has several other uses. In order to improve its utility in agriculture and allied sectors focused attention is required. Thus, there is an urgent need to address certain key issues in *Azolla* for its exploitation and better utilization. Concerted efforts are required from the part of policy makers, scientists and farmers to promote *Azolla* as a viable bioinoculant for sustainable crop production and development.

## REFERENCES

- Adhikari, K., Bhandari, S. and Acharya, S. 2020. An overview of *Azolla* in rice production: a review, *Food and Agriculture*, 2: 04-08.
- Akhtar, M., Sarwar, N., Ashraf, A., Ejaz, A., Ali, S. and Rizwan, M. 2020. Beneficial role of *Azolla* sp. in paddy soils and their use as bioremediators in polluted aqueous environments: implications and future perspectives. *Archives of Agronomy and Soil Science*, 3: 1-14.
- Ali, S., Naima, H., Dilrosh, K. and Kauser, A. M. 1998. Use of *Azolla* as biofertilizer to enhance crop yield in a rice—wheat cropping system under mild climate. Nitrogen Fixation with Non-Legumes. *Part of the Developments in Plant and Soil Sciences book series*, 79, 353–357.
- Anjuli, P., Radha, P. and Singh, P.K. 2004. Biological significance of *Azolla* and its utilization in agriculture. *Proceedings of the Indian National Science Academy, Biological Sciences*, 70 (3): 299–333.

- Anonymous, 1975. Cultivation, Propagation and Utilization of *Azolla*. Chekiang Agriculture Academy, *Institute of Soils and Fertilizers*, 9.
- Atieno, M., Herrmann, L., Nguyen, H.T., Phan, H.T., Nguyen, N.K., Srean, P. and Lesueur, D. 2020. Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. *Journal of Environmental Management*, 275.
- Atreya, K. 2015. In search of sustainable agriculture: A review of national policies relating to organic agriculture in Nepal, *Asia Network for Sustainable Agriculture and Bio resources*.
- Barthakur, H.B. and Talukdar, H. 1983. Use of *Azolla* and commercial nitrogen fertilizer in Jorhat, India. *International Rice Research Newsletter*, 8: 20–21.
- Bhardwaj, K.K.R. and Gaur, A.C. 1970. The effect of humic and fulvic acids on the growth and efficiency of nitrogen fixation of *Azotobacter chroococcum*. *Folia Microbiologica*, 15 (5): 364–367.
- Bhusal, D. and Thakur, D.P. 2021. Curry Leaf: A Review. *Reviews in Food and Agriculture*, 2 (1): 31–33.
- Bhuvaneshwari, K. 2012. Beneficial effects of blue green algae and *Azolla* in rice culture. *Environment Conservation*, 13(1): 1-5.
- Bhuvaneshwari, K. and Kumar, A. 2013. Agronomic potential of the association *Azolla-Anabaena*. *Science Research reporter*: 3(1) 78-82.
- Bhuvaneshwari, K. and Singh, P.K. 2015. Response of nitrogen-fixing water fern *Azolla* biofertilization to rice crop. *3 Biotech*, 5 (4): 523–529.
- Biswas, M., Parveen, S., Shimozawa, H. and Nakagoshi, N., 2005. Effects of *Azolla* species on weed emergence in a rice paddy ecosystem. *Weed Biology and Management*, 5 (4): 176–183.
- Chen, J. H. 2006. The combined use of chemical and organic fertilizers and/or biofertiliser for crop growth and soil fertility, International Workshop on Sustained Management of the Soil-Rhizosphere System for Efficient Crop Production and Fertilizer Use, 16 – 20 October, Land Development Department, Bangkok, Thailand.
- Damrongchai, N. 2000. Agricultural Biotechnology. *Biotechnology and Development: Challenges and Opportunities for Asia*, 201.
- De Macale, M.A.R. and Vlek, P.L.G. 2004. The role of *Azolla* cover in improving the nitrogen use efficiency of lowland rice. *Plant and Soil*, 263 (1): 311–321.
- Dey, S., Dasgupta, S., Chandra, B., Viswavidyalaya, K., Mondal, S., Chandra, B. and Gupta, S. 2018. Experimental approach for improvement of soil fertility by dose administration of chemical and organic fertilizers in Kharif rice field. *Journal of Plant Development Sciences*, 10 (4) : 225-230.
- Eames, A. J. 1936. Morphology of Vascular Plants. *McGraw Hill Book Co*, New York.

- Francisco, C., Generosa, T. and Diniz, M. A. 2000. *Azolla* as a biofertilizer in Africa, A challenge for the future. *Revista de Ciências Agrárias*, 23 (3): 120-138.
- Ghosh, B.C. and Bhat, R., 1998. Environmental hazards of nitrogen loading in wetland rice fields. *Environmental Pollution*, 102 (1): 123-126.
- Gnanavel, I., 2015. Eco-friendly weed control options for sustainable agriculture. *Science International (Dubai)*, 3 (2): 37–47.
- Gopalaswamy, G. and Kannaiyan, S. 2000. Influence of phosphorus on the growth of *Azolla* hybrids. *Proceedings of National Seminar on Agricultural Scenario Challenges and opportunities*. College of Agriculture, Gwalior, Madhya Pradesh: 55-56.
- Goswami, A., Ghosh, L. and Banerjee, R. 2014. The lacuna between R&D and technological commercialization of Biofertilizers in South Asian countries. *Journal of Advanced Research in Microbiology*, 1 (1): 28–46.
- Gupta, A. and Sen, S. 2013. Role of biofertilisers and biopesticides for sustainable agriculture, scholar.google.com.
- Gupta, V.K. and Potalia, B.S. 1990. Zinc-cadmium interaction in wheat. *Journal of the Indian Society of Soil Science*, 38 (3): 452–457.
- Halder, D. and Kheroar, S. 2013. Mineralization and Availability of *Azolla* and Cyanobacteria Biomass Nutrients in Rice Soil. *Journal of Agricultural Science and Technology*, 3 (3): 782–789.
- Hills, L. V. and Gopal, B. 1967. *Azolla primaeta* and its phylogenetic significance. *Canadian Journal of Chemistry*, 45: 1179-1191.
- Indrani, Y., Abdullah, R., Ansari, A. and Ori, L., 2019. Vermicomposting of different organic materials using the epigeic earthworm *Eisenia foetida*. *International Journal of Recycling of Organic Waste in Agriculture*, 8: 23-36.
- Islam, A., Molla, A.L. and Hoque, S., 1984. *Azolla* and blue-green algae as alternative sources of nitrogen for rice and their mineralization in soils of Bangladesh. *Indian Journal of Agricultural Science*, 54 (12): 1056-1060.
- Janiya, J.D. and Moody, K. 1984. Use of *Azolla* to suppress weeds in transplanted rice. *International Journal of Pest Management*, 30 (1): 1–6.
- Kandel, S., Malla, R., Adhikary, B.H. and Vista, S.P., 2020. Effect of *Azolla* Application on Rice Production at Mid-Hills Condition of Nepal. *Tropical Agroecosystems*, 1 (2): 103-106.
- Kannaiyan, S. 1993. Nitrogen contribution by *Azolla* to rice crop. *Biological Science*, 59: 309-314.
- Kannaiyan, S. and Kalidurai, M. 1995. Nitrogen fixing potential of stem nodulating *Sesbania rostrata* and its effect on rice yield. *Rice Management Biotechnology*, 5: 173-195.

- Kannaiyan, S. and Rejeswari, N. 1983. Comparative effect of fertilizer nitrogen and *Azolla* biofertilizer on tiller production of rice. *Science and Culture*, 45: 245-246.
- Kannaiyan, S. and Subramani, S. 1992. Use of *Azolla* as biofertilizer for rice crop, Cyanobacterial Nitrogen Fixation. *Indian Agricultural Research Institute*, 4: 281-289.
- Konar, R. N. and Kapoor, R. K. 1972. Anatomical studies on *Azolla pinnata*. *Phytomorphology*, 22: 211-223.
- Krishnakumar, S., Saravanan, A., Natarajan, S. K., Veerbadaran, V. and Mani, S. 2005. Microbial population and enzymatic activity as influenced by organic farming. *Research journal of Agriculture and Biological Science*, 1: 85-89.
- Kulasooriya, S. A., and R. S. Y. de Silva. 1977. Effect of *Azolla* on yield of rice. *International Rice Research*, 2: 10-15.
- Kumar, K. and Kannaiyan, S. 1992. Changes in the activity of soil enzymes during decomposition of N fixing green manures. 33<sup>rd</sup> Annual Conference of Association of Microbiologists of India, Goa University, India.
- Kumarasinghe, K. S. and Eskew, D. L. 1995. *Azolla* as a Nitrogen Fertilizer in sustainable rice production, 7: 147-154
- Le Van, K. 1963. The problems of the utilization of *Azolla* as a green manure in the Democratic Republic of Vietnam. Timui. Moscow. *Academy of Agriculture Journal*, 94: 93-97.
- Lumpkin, T. A and Plucknett, D. L. 1980. *Azolla*: Botany, Physiology and use as a green manure. *Economic Botany*, 34: 111-153.
- Lumpkin, T. A. and Plucknett, D. L. 1982. *Azolla* as a green manure; use and management in crop production. Westview Press; Boulder, Colorado, USA Westview Press Boulder Colorado, 15: 230,
- Manna, A.B. and Singh, P.K. 1990. Growth and nitrogen fixation of *Azolla pinnata* and *Azolla caroliniana* as affected by urea fertilizer and their influence on rice yield. *Plant and Soil*, 122 (2): 207-212.
- Mishra, D.J., Rajvir, S., Mishra, U.K. and Kumar, S.S. 2013. Role of Bio-Fertilizer in Organic Agriculture: A Review. *Research Journal of Recent Sciences*, 2: 39-41.
- Mishra, P. and Dash, D. 2014. Rejuvenation of Biofertilizer for Sustainable Agriculture and Economic Development. *The Journal of Sustainable Development*, 11 (1): 41-61.
- Moore, A. W. 1969. *Azolla*: biology and agronomic significance. *The Botanical review*, 35: 17-35.
- Nayak, S. K and Singh, P. K .1988. Some variation in dermal appendages of *Azolla*. *International Journal of Ferns*, 5: 170-175.

- Nayak, S., Prasanna, R., Pabby, A., Dominic, T. K. and Singh, P. K. 2004. Effect of urea, blue green algae and *Azolla* on nitrogen fixation and chlorophyll accumulation in soil under rice. *Biology and fertility of soils*, 40(1), 67-72.
- Ngo, G. 1973. The effect of *Azolla pinnata* R. Br. on rice growth. *Biotrop Report—Second Indonesian Weed Science Conference*, Jogjakarta.
- Nosheen, S., Ajmal, I. and Song, Y., 2021. Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability* 13, 1–20.
- Pereira, A.L. 2017. The Unique Symbiotic System between a Fern and a Cyanobacterium, *Azolla-Anabaena Azollae*: Their potential as biofertilizer, feed, and remediation. In *Symbiosis. Intech Open London*, UK.
- Peters, G. A and Meeks, J. C. 1989. The *Azolla-Anabaena* symbiosis: basic biology. *Annual Review of Plant Physiology and Plant Molecular Biology*, 40: 193-210.
- Peters, G. A. and Mayne, B. C. 1974 The *Azolla, Anabaena azollae* Relationship: I. Initial Characterization of the Association. *Plant Physiology*, 53: 813-819.
- Rai, A.N., Singh, A.K. and Syiem, M.B., 2018. Plant Growth-Promoting Abilities in Cyanobacteria. *Basic Science to Applications*, 5: 23.
- Raja, W., Preeti, R., Suchit. A. J. and Pramood, W. R. 2012. *Azolla*: An aquatic pteridophyte with great potential. *International Journal of Research in Biological Sciences*, 2(2): 68-72.
- Razavipour, T., Moghaddam, S.S., Doaei, S., Noorhosseini, S.A. and Damalas, C.A., 2018. *Azolla (Azolla filiculoides)* compost improves grain yield of rice (*Oryza sativa* L.) under different irrigation regimes. *Agricultural Water Management*, 209: 1-10.
- Rivaie, A.A., Isnaini, S. and Maryati, 2013. Changes in soil N, P, K, rice growth and yield following the application of *Azolla pinnata*. *Journal of Biology, Agriculture and Healthcare*, 3 (2): 112–117.
- Roger, P.A., 1999. Use of blue-green algae and *Azolla* in rice culture.
- Rosegrant, M.W., Roumasset, J.A. and Balisacan, A.M. 1985. Biological Technology and Agricultural Policy: An Assessment of *Azolla* in Philippine Rice Production. *American Journal of Agricultural Economics*, 67 (4): 726–732.
- Safriyani, E., Hasmeda, M., Munandar, Sulaiman, F., Holidi. and Kartika, K. 2020. The role of *Azolla* on improving nitrogen efficiency in rice cultivation. *Iranian Journal of Plant Physiology*, 10 (2): 3095-3102.
- Sahrawat, K. L. 1983. Mineralization of soil organic nitrogen under waterlogged conditions in relation to other properties of rice soil. *Plant Soil*, 42: 305-308.
- Samal, K.C., Behera, L. and Sahoo, J.P. 2020. *Azolla* Biofertilizer -The Nature's Miracle Gift for Sustainable Rice Production, *Biotica Research Today*, 2(9), 971-973.

- Samarajeewa, K., Kojima, N., Sakagami, J. and Chandanie, W.A., 2005. The effect of different timing of top dressing of nitrogen application under low light intensity on the yield of rice (*Oryza sativa* L.). *Journal of Agronomy and Crop Science*, 191 (2): 99-105.
- Santhiya, B. and Jeeva, S. 2002. Effect of certain conventional bioregulators on reclamation of chemical contaminated croplands – a literature review. *Journal of Xi'an Shiyou University, Natural Science Edition*, 18(11): 8-20.
- Setiawati, M.R., Suryatmana, P., Budiasih, S. N., Nurlina, L., Kurnani, B.A. and Harlia, E., 2018. Utilization *Azolla pinnata* as substitution of manure to improve organic rice yield and paddy soil health. IOP Conference Series: *Earth and Environmental Science*, 215 (1).
- Shen, C. S., Lu, K., Chen, K. and Ge, S. 1963. The initial experiment of *Azolla's* nitrogen fixing ability. Turang Tongbao (Pedology Bull.). *Peking*, 4: 46-48.
- Singh, P. K. 1988. Biofertilization of rice crop, Biofertilizers: Potential and Problems, *Plant Physiology Forum*: 109-114.
- Singh, P.K. 1977. Multiplication and utilization of fern *Azolla* containing nitrogen fixing algal symbiont as a green manure in rice cultivation. *Riso*, 46: 642-644.
- Small, E. and Darbyshire, S. J. 2011. Mosquito Ferns (*Azolla* species)–tiny ‘super plants’, *Biodiversity*, 12(2): 119-128.
- Subedi, P. and Shrestha, J. 2015. Improving soil fertility through *Azolla* application in low land rice: A review. *International System for Agricultural Science and Technology*, 2 (2): 35–39.
- Sureshkumar, R., Reddy, Y.A. and Ravichandran, S. 2016. Effect of weeds and their management in transplanted rice—a review. *International Journal of Research in Applied, Natural and Social Sciences*, 4 (11): 165-180.
- Svenson, H. K. 1944. The new world species of *Azolla*. *American Journal of Ferns*, 61: 1-13.
- Talley, S. N., Talley, B. J. and Rains, D. W. 1977. Nitrogen fixation by *Azolla* in rice fields. In Alexander Hollaender, ed. *Genetic Engineering for Nitrogen Fixation*. Plenum Press, New York and London: 259-281.
- Thangaraju, M. and Kannaiyan, S. 1989. Studies on the urease activity and fertility status of soil by incorporating certain *Azolla* cultures. *29<sup>th</sup> Annual Conference Association Microbiologists of India*: 87.
- Thanikachalam, A., Rajakannu, K. and Kannaiyan, S. 1984. Effect of neem cake, carbofuran and *Azolla* application on phosphatase activity in soil. *25<sup>th</sup> Annual Conference of Association of Microbiologists of India*, GB Pant University of Agriculture and Technology, Pant Nagar, India
- Thapa, P. and Poudel, K. 2021. *Azolla*: Potential Biofertilizer for Increasing Rice Productivity, And Government Policy for Implementation. *Journal of Wastes and Biomass Management*, 3(2): 62-68.

- Tran, Q.T. and Dao, T. 1973. *Azolla*: A green compost. *Journal of Agronomy and Crop Science*, 4: 119-127.
- Van, H. C. 1989. *Azolla* and its multiple uses with emphasis on Africa, *Food and Agricultural Organization*, Rome.
- Wang, D.X., Zhao, M.Z. and Chen, D.F. 1987. Studies on the mineralization rate and nutrient releasing dynamics, *Azolla* utilization. *Proceedings of Workshop on Azolla use*: 275, International Rice Research Institute, LosBanos, Philippines.
- Watanabe, I. 1977. *Azolla* utilization in rice culture. *International Rice Research Newsletter*, 2: 3-8.
- Watanabe, I., Ventura, W., Mascariña, G. and Eskew, D.L. 1989. Fate of *Azolla* spp. and urea nitrogen applied to wetland rice (*Oryza sativa* L.). *Biology and Fertility of Soils*, 8 (2): 102-110.
- West, R.G.1953. The occurrence of *Azolla* in the British interglacial deposits. *New Phytology*, 52: 267-271.
- Yadav, R. K., Abraham,G., Singh, Y. V. and Singh,P.K. 2014. Advancements in the Utilization of *Azolla-Anabaena* System in Relation to Sustainable Agricultural Practices. *Proceedings of the Indian National Science Academy*, 2: 301-316.
- Yao, Y., Zhang, M., Tian, Y., Zhao, M., Zeng, K., Zhang, B. and Yin, B. 2018. *Azolla* biofertilizer for improving low nitrogen use efficiency in an intensive rice cropping system. *Field Crops Research*, 216: 158-164.
- York, N. and Garden, B., 2016. *Azolla*: Botany, Physiology, and Use as a Green Manure. *Springer*, 34: 111-153.
- Zhang, H., Li, H., Li, X., Li, Z., 2014. Temporal changes of nitrogen balance and their driving factors in typical agricultural area of Lake Tai Basin. *Chinese Journal of Soil Science*, 45 (5): 1119–1129.