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A Review of *Azolla* spp. as a Potential Resource for Sustainable Agriculture in Sri Lanka: A New Effort for the Green Agriculture among Sri Lankan Farmers

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Abstract

The present economic crisis in Sri Lanka has limited the usage of inorganic fertilizers in agriculture sector. Furthermore, animal husbandry, the other branch of agriculture has problems due to high prices of animal feed and unavailability. The concept of using *Azolla* spp. as a multifaceted resource for sustainable agriculture, which facilitates the environment-friendly green concept, is receiving great attention in the present crisis. *Azolla* is a small floating, fast-growing aquatic fern distributed globally. Because of its growth habitat, high biomass production and nitrogen-fixing ability, it has acquired substantial value in the agriculture sector, especially as a nitrogen supplier to plants. Besides its usage as a fertilizer, *Azolla* can be used as a nutrient provision for animals, human food, phyto-remediating agent, weed controller, mosquito controller, medicinal plant, and a substrate for biogas production. It is a feed rich in protein, which can be used to feed farm animals, poultry, and fish. As well, it is found to be a more affordable additional feed supplement for the animals. The nitrogen-fixing ability of *Azolla* with the aid of a symbiotic cyanobacterium *Anabaena azollae* has led to the exploitation of *Azolla* as an effective nitrogen fertilizer and a protein supplier. Also, it helps to conserve water, sequestrate carbon, and appropriate for integrated farming systems. *Azolla* is grown in many countries for the aforementioned uses and its cultivation aligns with the goals of sustainable and environmentally conscious agriculture. *Azolla* can be easily grown in containers, soil pits or cement tanks that hold water. The required conditions should be supplied, including optimum light intensity, relative humidity, pH, salinity macro and micronutrients, etc. This review addresses the morphology of *Azolla*, its symbiotic relationship, and the potential usages for sustainable agriculture as a new effort for the green agriculture among Sri Lankan farmers.

Keywords: *Azolla* spp., Biofertilizer, Green Manure, Nitrogen Fixation, Sustainable Agriculture

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INTRODUCTION

As a consequence of the green revolution, farmers tend to apply a huge amount of synthetic fertilizers to fulfill food and nutrition requirements. Farmers in Sri Lanka also have predominantly used synthetic fertilizers for decades expecting rapid prospects in agriculture. However, the synthetic fertilizer application boom has caused many environmental problems and diminished human health in Sri Lanka. At the same time, the recent economic crisis in Sri Lanka has created a serious barrier for importing agricultural inputs. Hence, limited resources such as fertilizer, animal feed and other agrochemicals have created low agricultural production and failed to sustain farmers in the agriculture sector. Therefore, the calamity of the agriculture sector in Sri Lanka cannot be avoided, hence using alternative resources is one of the strategies to overcome the present economic turmoil.

Fertilizer application is one of the management practices that should operate sustainably. Fertilizer usage affects soil nutrient availability, the yield of crops, agriculture production and the environment [1]. Synthetic fertilizer usage for agricultural purposes may be uneconomical, inefficient, and unsustainable, because of nitrogen losses as ammonia or nitrous oxide and methane production from flooded lands [2]. Therefore, there should be sustainable methods for fertilizer application. The green concept in Agriculture arises as a viable solution in this context. At this point, bio-based fertilizers play a major role in sustainable agriculture, while providing nutrients and mitigating negative impacts on the environment. Therefore, it is time to evaluate the prospectus of these fertilizers for sustainable agriculture in Sri Lanka.

Green development in agriculture relates to the concept of sustainability and it is a holistic approach that maintains the balance between the environment and socio-economic impacts. The concept of sustainability was advanced in Neo-Malthusianism discourses during the 1960s and 1970s. The aim of this concept is to accentuate the well-being of the natural ecosystems [3]. Sustainable agriculture is simply, meeting the present needs without depleting the resources on the earth, which aids to meet future needs. Therefore, sustainable agriculture can be defined as a commitment to fulfill food and fiber needs and also to uplift the living standards of the farmers and society, now and in the future [4].

Organic substances such as green manure can be employed as alternative nutrient sources instead of commercial synthetic fertilizers [6]. Green manuring is the addition of green plant tissues into the soil [5], which is inexpensive and environmentally friendly. Green manures that have high nutrient availability and low C/N ratios make significant impacts as fertilizers [1]. Green manure from legumes is a feasible source of nitrogen fertilizer. There are several critical factors for the selection of green manure crops, such as fast-growing ability, succulent nature, adaptability to a broad range of environmental conditions and nitrogen fixation [7]. The average nitrogen accumulation in green manures can substitute the nitrogen availability of synthetic fertilizer at average application rates [1]. The addition of green manure contributes 30 to 100 kg N ha^{-1} and in many instances, it is about 50 to 60 kg N ha^{-1} [5].

Besides nitrogen, green manuring enhances the availability of phosphorus via several mechanisms of reduction, chelation and satisfactory alterations in pH. Also, it helps the mobilization of a wide variety of elements, including sulfur, phosphorus, silicon, zinc, manganese and copper, etc. as a consequence of enhanced microbial activities and diminished redox potential. Furthermore, it decreases the bulk density, while increasing the stability of water-stable aggregates, pore spaces, water intake and water retention [5]. Moreover, green manure application helps to maintain or build organic matter in the soil-plant environment, thus improving the soil structure, water holding capacity, size of pores and efficiency of inorganic fertilizer usage [8]. Among the various green manures, *Azolla* has arisen as a

feasible solution in many countries, especially in Taiwan, China, Philippines, India and Indonesia. However, the usage of this plant in the agriculture sector is not much popular among Sri Lankan farmers. Therefore, this article aims to discuss the potential usage of *Azolla* in sustainable agriculture, as a green fertilizer.

Distribution of *Azolla* Spp.

The term *Azolla* is derived from the Greek words *azo* (to dry) and *ollymi* (to kill), suggesting the meaning of death from drought [9]. *Azolla* domestication was in the 11th century and first reported in Vietnam [10] and now it is distributed worldwide. *Azolla* belongs to the genus of aquatic ferns, which primarily exists in tropical and warm temperate zones [11]. It is a free-floating, dichotomously branched, aquatic fern that is naturally existing in wet soils, ditches and marshy ponds [12]. Several *Azolla* species have been domesticated throughout the world, including *A. pinnata*, *Azolla caroliniana*, and *A. microphylla* which are found in the Indian subcontinent [13].

Water is an essential component for the survival of *Azolla* spp. and it floats on the surface of water to survive [10]. *Azolla pinnata* can grow under nitrogen-deficit conditions because it has the ability to intake atmospheric nitrogen and grow without any nitrogen sources [14]. The nitrogen requirement of *Azolla* has accomplished itself through nitrogen fixation, but macro and micronutrients are required for its development [2]. The major limiting nutrient for *Azolla* growth is phosphorus [15]. Besides nitrogen and phosphorus, other macronutrients such as potassium, calcium and magnesium are also required for its growth [10]. In addition, it necessitates micronutrients such as molybdenum, manganese, zinc, copper, iron and cobalt. Also, light intensity affects its optimum growth and the optimal light intensity for *Azolla* growth is 15-18 klux, but high light intensities inhibit photosynthesis and growth of *Azolla*. Furthermore, its productivity depends on the relative humidity, nutrients, pH, salinity, wind and growing season. Near neutral pH and high amount of phosphorus in water body facilitates the growth of *Azolla* spp. [10].

Azolla caroliniana is mostly cultivated in high humidity (80-90%) and low light intensity (50%) conditions. Further, it is reported from environments with high nitrogenase activity [16]. Winds and waves cause vulnerable to disruption in water surfaces for the growth of *Azolla* spp. because of the free-floating nature of the plant and agitation of water, which can break the fronds leading to low absorption efficiencies of nitrogen [10]. Vegetative reproduction of *Azolla* spp. occurs by division of the abscission layer at the base of each branch, while sexual reproduction is uncommon and is influenced by environmental factors such as several stress conditions [11, 17].

Figure 1: *Azolla pinnata* Grown as a Mat on the Water Surface

Morphological Characters of *Azolla* Spp.

Azolla fronds are floating parts on the surface of water and are triangular or polygonal in shape. These fronds range from 1-2.5 cm in length in small species such as *A. pinnata* and 15 cm or more in large species such as *A. nilotica*. It has a main stem that is branched into secondary stems, which bear small leaves that have an alternate leaf arrangement. The unbranched, adventitious roots fall down into the water that arise from nodes on the ventral surfaces of the stems. Furthermore, each *Azolla* leaf comprises with two lobes. The aerial dorsal lobe is chlorophyllous and the partially submerged ventral lobe is cup-

shaped, colourless and provide buoyancy for the plant [18-20]. Figure 1 shows the *Azolla pinnata* grown in an artificial pond.

Symbiotic Relationship of *Azolla* Spp.

No plant individually can fix nitrogen and use it directly for plant growth unless from a symbiotic association [21]. *Azolla* often makes symbiotic associations with blue-green algae or cyanobacteria, *Anabaena azollae,* which aids to fix and assimilate atmospheric nitrogen [22]. The cyanobacteria live and reproduce in the leaf cavities; however, the association remains extracellular [21]. *Azolla-Anabaena* symbiotic relationship has a capability to fix atmospheric nitrogen rapidly, thus enabling the cultivation of rice under tropical conditions. Also, it has led to the exploitation of *Azolla* as a biofertilizer. The enhanced nitrogen fixation is linked with the production of high biomass of *Azolla* [23]. As shown in Figure 2, *A. azollae* which live within the dorsal lobe of the leaf cavity or 'hairs' of *Azolla*, converts atmospheric nitrogen into usable forms of nitrogen with the aid of nitrogenase enzyme.

The Figure 3 illustrates the microscopic view of *A. azollae*, which live in the *Azolla* leaf cavities. Within the leaf cavities, *A. azollae* are protected and under a micro-aerophilic (low-oxygen) environment, the optimal functioning of the nitrogenase enzyme produced by *A. azollae* occurs. The leaf cavities of *Azolla* maintain a balance between aerobic and anaerobic conditions, where *A. azollae* perform photosynthesis during daylight, producing oxygen, while nitrogen fixation occurs in the absence of light or in shaded conditions, reducing the oxygen concentration. On the other hand, the *Azolla* plants are benefited by the fixed nitrogen to enhance its growth and development. According to the figure 2, the atmospheric N_2 is converted into ammonium through this process.

Beneficial Aspects of *Azolla*

Among many other benefits of *Azolla*, the potentiality of using it as a biofertilizer is popularizing in the present scenario. *Azolla* can be used as an effective biofertilizer, and as a source of nitrogen due to its nitrogen-fixing ability. Biological nitrogen fixation is an environmental friendly mechanism that fulfills nitrogen requirements [20]. Different beneficial aspects of *Azolla* are discussed below.

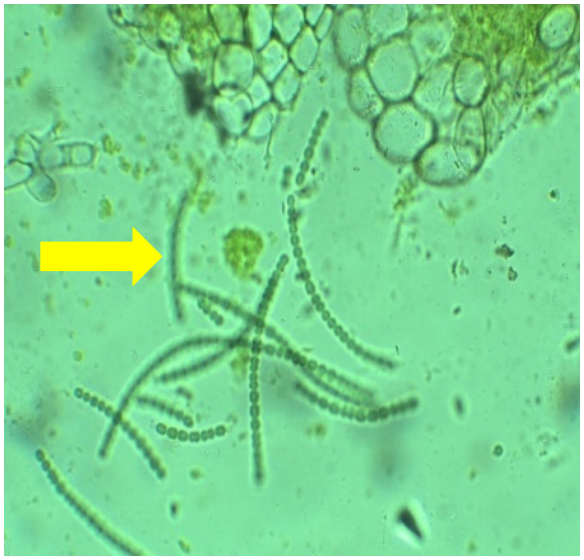

Figure 3: Microscopic View of *Anabaena azollae*

Azolla as a Nitrogen Fertilizer

Azolla is a good biofertilizer and green manure that is distributed globally [23]. Several studies have reported that *Azolla* enhances crop yield [24]. *Azolla* as an effective biofertilizer, reduces the negative impacts of synthetic fertilizers on long-term soil fertility, while enhancing the soil fertility [12] due to increment of total nitrogen, organic carbon and phosphorus availability [17, 25]. The average nitrogen fixing rate can range between 1.0 to 2.6 kg N ha^{-1} day^{-1} [16]. Nitrogen is a vital element for proteins, nucleic acids and other organic nitrogenous composites [21].

Azolla-Anabaena symbiosis provides nutrition requirements for various plant species including rice, wheat and taro etc. [20]. It can be an effective biofertilizer for many crop species other than paddy, especially for crops that grow in a flooded soil ecosystem such as Colocasia esculenta (taro) [25]. azolla application as a mulch for bananas is also practiced [25].

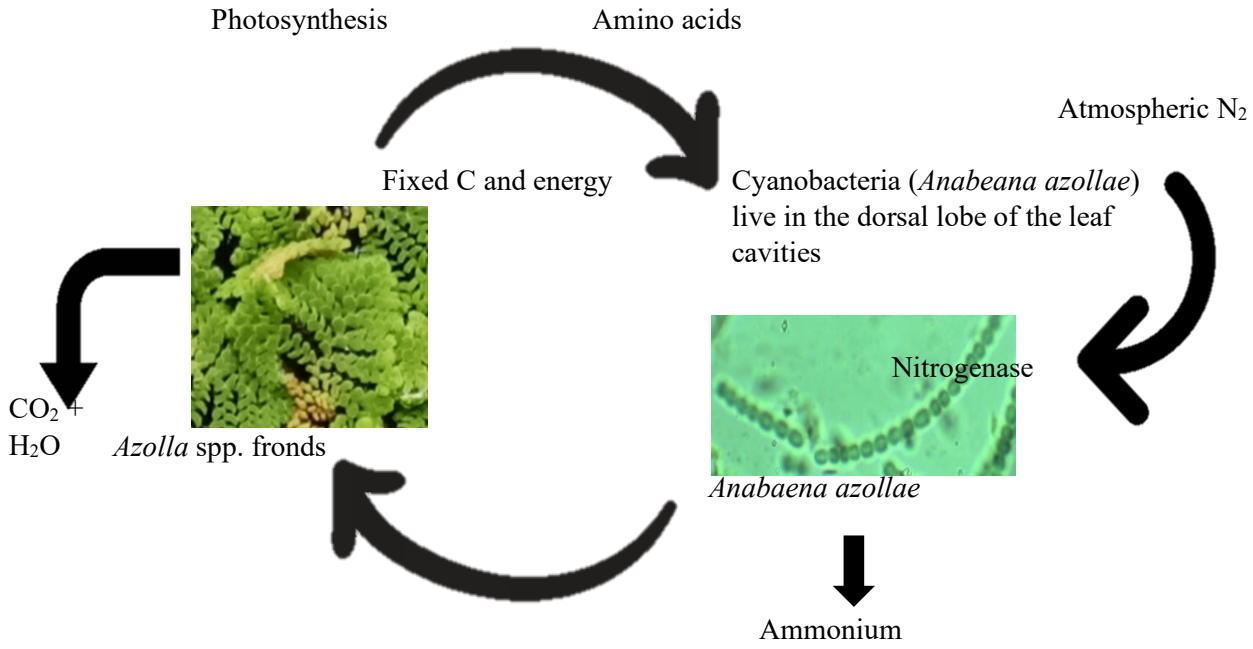

Figure 2: The Process of the *Anabaena azollae* Symbiotic Relationship with *Azolla* spp.

Nitrogen is a vital element for proteins, nucleic acids and other organic nitrogenous composites [21]. *Azolla-Anabaena* symbiosis provides nutrition requirements for various plant species including rice, wheat and taro etc. [20]. It can be an effective biofertilizer for many crop species other than paddy, predominantly for crops that grow in a flooded soil ecosystem such as *Colocasia esculenta* (taro) [25]. *Azolla* application as a mulch for bananas is also practiced [25].

It can be considered as a possible source of organic manure and nitrogen in paddy cultivation because it comprises of 0.2-0.4% nitrogen on a wet basis and 4-5% on a dry basis [26]. *Azolla* as the basal application of 10-12 tones ha^{-1} improves nitrogen in soil by 50-60 kg ha^{-1} and decreases the nitrogen fertilizer necessity by 30-35 kg [16]. Also, *Azolla* has proven to produce twice as a dual crop in rice at 500 kg ha^{-1}, while improving the soil nitrogen by 50 kg ha^{-1} and cutting the nitrogen requirement by 20-30 kg ha^{-1}. The usage of *Azolla* enhances rice productivity by 20 to 30% [16]. *Azolla* association with rice and fish-integrated farming in China, has enhanced the rice yield by 20% and fish production by 30% [22]. Vegetative reproduction is prominent in *Azolla* thus the biomass should be maintained throughout the year [23] to use it as an effective fertilizer. *Azolla* improves the nutrient availability of soil through a biological activity that aids to construct the microflora for mineralization [27].

There are three basic procedures for applying *Azolla* to crops. First, *Azolla* grows as a single crop in the fallow period and then mixes with soil before planting the targeted plant species. Secondly, growing *Azolla* as an intercrop can be practiced. Thirdly, *Azolla* cultures maintained in swamps, ponds, or flooded fields can be harvested and applied for target crops. These applications can be done either by incorporating harvested *Azolla* into the soil before planting or by using it as a mulch. A combination of the above procedures also can be practiced [19]. The

most common method of *Azolla* application is as a green manure application collected from ponds and ditches or growing as a dual crop with the paddy [23]. *Azolla* cultivation in rice fields either as a monocrop or as an intercrop is practiced in India, China, Philippines and Indonesia etc. [13]. It is very effective in biomass accumulation and nitrogen-fixing ability which required low-skill and low-cost.

Research and Development regarding Azolla Spp. as a Green Manure for Different Crop Varieties

Table 1 describes different research studies conducted for the usage of *Azolla* spp. for different crop varieties.

Azolla as a Nutrient Supplement for Animals

Azolla has the potential to be used as a feeding ingredient for cattle, goats, pigs, rabbits, chickens, fish and ducks, etc. [13]. *Azolla* meal consists of 21.4% crude protein, 12.7% crude fiber, 2.7%, ether extract, 16.2% ash and 47.0% carbohydrate in dry form [36]. *Azolla* has a substantial amount of proteins, essential amino acids, growth promoter mediators, vitamins (vitamin A, vitamin b12, Beta Carotene) and minerals (Ca, P, K, Fe, Cu, Mg). Furthermore, *Azolla* has a low carbohydrate and oil content. Therefore, it is an economical and effective feeding substitute for livestock [22].

A. pinnata can be considered as an alternative feed ingredient for the poultry industry [37]. High protein and less lignin content can result in easy digestion of *Azolla* [22], while the gross energy value of *Azolla* is 2039 kcal kg^{-1} [36]. *Azolla* as a feed ingredient, increases the weight of broilers and improves the production of eggs in layers. Also, it provides a solution for the cost of production due to high feed costs [22]. *Azolla* is a suitable source of protein that can be used up to 5% in broiler ration, with no deleterious effects on the palatability of diets. These results are based on an experiment conducted using 120 Vencobb commercial broilers. Also, the amount of *Azolla* in the ration does not have any effect on the nutrient digestibility of crude protein, crude fat and crude fiber.

Furthermore, broilers have an ability to readily digest the crude fiber in *Azolla,* but not that in rice bran [37]. Hence digestibleness cannot be considered as a limiting factor for *Azolla* meals [38]. The combination of 1.5-2 kg of *Azolla* with regular feed has been reported to increase milk production by 15-20% in dairy animal trials in Tamil Nadu and Kerala [22]. Further, *Azolla* can be used as a fish meal for a variety of commercial fish species, Nile tilapia (*Oreochromis niloticus*), Mozambique tilapia (*Tilapia mossambica*), Redbelly tilapia (*Tilapia zillii*), Rohu (*Labeo rohita*), South Asia carp (*Catla catla*), orange fin labeo (*Labeo calbasu*), Fringed-lipped peninsula carp (*Labeo fimbriatus*), Grass carp (*Ctenopharyngodon Idella*) and Java barb (*Barbonymus gonionotus*) and many works of literature has reported that adding *Azolla* spp. up to a certain level enhances the growth, feed consumption and survival rate of *Oreochromis niloticus* [39].

Azolla as a Potential Source of Human Food

Azolla has been suggested to be fit for human consumption [25]. Its protein content is somewhat similar to soybean and it contains 10-15% minerals and 7-10% essential amino acids on a dry weight basis. Moreover, it has vitamins and carotenoids [13]. It is used as a salad in Western countries because of its high protein amount [12]. Several experiments have been carried out on the use of *Azolla* as soups and meatballs; which requires further development [40]. Also, there is potential to use *Azolla* as a diet for space stations, space travel and habitation on the Mars and Moon [13]. Studies on consumption potential of *Azolla* app. as a human food would be advantageous as a nutrients and protein supplying substitute in future.

Azolla as a Phytoremediation Agent

Phytoremediation is a green technology that uses either naturally occurring specially selected or genetically engineered plants to decontaminate polluted environmental systems [41]. Industrial activities including paper production, electroplating, printing, soft drinks, oil, pesticide, paints, and pharmaceuticals production can produce a high volume of wastewater [14]. *Azolla* has decent phytoremediation potential, due to its

Table 1: Research on the usage of *Azolla* for Different Crop Varieties

***Azolla* Species**	**Crop**	**Application**	**Results**	**Reference**
A. pinnata	Squash	Wheat straw and five fertilizer treatments were (control, chemical fertilizer; N 112 kg/ha, P_2O_5 75 kg/ha, and K_2O 75 kg/ha, compost; 7.5 t/ha, vermicompost; 7.5 t/ha and dry *Azolla*; 3.75 t/ha) added to the soil.	The soil treated with *Azolla pinnata* and covered with wheat straw showed the greatest significant levels of accessible N, P and K.	[28]
A. caroliniana	Rice	A pot experiment was carried out using soil, biofertilizer and commercial N, P and K chemical fertilizer. The biofertilizer was prepared by mixing soil with *A. caroliniana*.	*A. caroliniana* has been recommended as a replacement for chemical nitrogenous fertilizer.	[29]
A. pinnata	Rice	Fresh *A. pinnata* has been applied at doses of 0-, 10- and 20-ton ha^{-1} and *A. pinnata* as compost powder at 2.5 ton ha^{-1} and 5 ton ha^{-1}.	Integration of fresh *A. pinnata* at 20 tons ha^{-1} and its compost powder at 5 tons ha^{-1} has improved the accessible P of soil, plant P content and number of tillers.	[30]
A. pinnata	Tomato	Different concentrations of *Azolla* extract (5%, 10%, 20%, 30%, 40%, and 50%) have been applied as a foliar application.	The 20% concentration has shown the highest germination percentage, shoot and root length, fresh and dry weights and highest effect on all vegetative growth parameters.	[31]
A. pinnata	Chinese kale	Application of *Azolla* bokashi fertilizer, consisting of three levels (control, 1.14 kg/plot, 2.28 kg/plot) and liquid organic fertilizer of goat manure (consisting of control, 100 ml/liter of water, 200 ml/liter of water, 300 ml/liter of water) has been investigated.	The administration of *Azolla* bokashi has shown the highest plant height and the chlorophyll quantity at the dose of 2.28 kg/plot.	[32]

A. pinnata	Red spinach	Application of five treatments (control, urea at 50 kg ha-1, poultry manure at 5 t ha-1, *Azolla* at the urea N rate of 23 kg N ha-1, and *Azolla* at the manure N rate of 108 kg N ha-1) in alluvial and peat soils has been investigated.	*Azolla pinnata* added as the manure N rate can be used as an alternative biofertilizer, especially for peat soil.	[33]
A. pinnata and *A. filiculoides*	Rice	Fresh *Azolla* has been used as a basal incorporation in soil and as a dual crop with rice separately, together with and without chemical nitrogen fertilizer in pots kept under net house conditions. (In basal treatments, it has been incorporated in soil before transplanting and equal shares of *A. pinnata* and *A. filiculoides* have been mixed for achieving a more stable plant growth)	Noticeable improvement in height of the plants, number of effective tillers, dry mass and nitrogen content of rice plants have been reported due to the use of *Azolla* and nitrogen fertilizers alone and other mixtures. The use of *Azolla* spp. has also enhanced organic matter and potassium contents of the soil.	[34]
Azolla spp.	Rice	*Azolla* has been used as a green manure and dual crop, while comparing with a commercial chemical fertilizer.	The results have shown that the yield, the number of tillers, plant height, profit to farmers, and the benefit to cost ratio of *Azolla* were higher than the chemical fertilizer.	[35]

high volume of wastewater [14]. *Azolla* has phytoremediation potential, due to its capability to concentrate heavy metals such as copper, cadmium, chromium, nickel, lead and nutrients directly from polluted water or sewage water [13, 16]. Phytoremediation technologies that use chemical chelates such as EDTA, DTPA might be unsustainable because these cause negative impacts on the soil and aquatic environment [2]. Therefore, utilization of *Azolla microphylla*, *A. pinnata* and *A. filiculoides* is more environmentally friendly and cost-effective [14, 41].

Azolla for Biofuel Production

Azolla is one of the rapid-growing plants on the earth, thus it can be considered as a potential source for bioenergy production. The chemical constituents of *Azolla* resemble combinations of terrestrial bioenergy crops and microalgae or cyanobacteria. In this context, *Azolla* is an attractive universal feedstock that is available at low cost, low energy demanding and near zero maintenance system for the production of biofuels [42]. The oil extraction amount from *Azolla* against another feedstock is acceptable as biodiesel [43]. *Azolla* or a combination of *Azolla* with rice straw can be fermented under anaerobic conditions thus results methane gas that can be utilized as a biofuel [20]. The ethanol production of *A. filiculoides* is about 11700 liters $ha^{-1}year^{-1}$ and it is close to the ethanol production from corn stover (13310 liters ha^{-1} $year^{-1}$), greater than from miscanthus (2300 liters ha^{-1} $year^{-1}$) and willow (300 liters ha^{-1} $year^{-1}$), while being lower than from sugarcane (25000 liters ha^{-1} $year^{-1}$) [42].

Azolla for Weed Control and Mosquito Control

Azolla cover can diminish the light intensity by around 90% and reduce photosynthesis in water. This can reduce the dissolved oxygen concentration of water by more than 50%. Besides, it alters the quality of light penetrating the water column. These effects can reduce the germination of light-sensitive seeds of different weeds [20]. Further, Azolla-incorporated rice fields have reported less weed levels, because of the *Azolla* dense cover on the surface of water. There are two possible mechanisms for weed suppression by *Azolla*; the most effectual method by the light-starvation of young seedlings of weeds [19] and by causing physical resistance to the emergence of seedlings of weeds due to dense *Azolla* mat, which does not affect the growth of rice [44].

Azolla forms a thick mat on the surface of water, which prevents mosquito breeding and adult emergence [12, 20]. According to previous studies, the breeding of *Anoplieles* spp. has been completely suppressed by the dense *Azolla* mats in water bodies [45]. *Azolla* is also recognized as the 'mosquito fern' due to its capability to reduce mosquito breeding.

Methods of Establishing Artificial Ponds to Grow A*zolla*

Azolla can be grown in artificial ponds or pits while providing optimum growing conditions. Artificial ponds can be created using concrete structures, rectangular or cylindrical in shape. Also, *Azolla* can be successfully grown in a pit of 7 to 10 inches deep, 3 feet wide, and 7-10 feet long. The pit should be placed in a shaded place [46-47] and should be covered using a plastic sheet to prevent leaching. In addition, 10-15 kg of soil, super-phosphate or animal dung (4-5 days old) should be added as a source of phosphorus. After, leaving the pit for 2-3 days to settle the soil, *Azolla* can be introduced. The addition of 2-3 kg of *Azolla* produces 1-3 kg of biomass daily after two weeks. Water (20-30%) should be changed every five days and super-phosphate or animal dung should be added. Also, the pit should be cleaned after 6 months to avoid the production of odours [47].

Limitations of Cultivating and using *Azolla*

Although Azolla has a prolific growth, the application rate of *Azolla* is 0.5 - 1.0 ton ha^{-1}, which limits the promotion of *Azolla* as a biofertilizer [48]. *Azolla* reproduction occurs mainly vegetatively, and this causes the necessity of maintaining *Azolla* biomass throughout the year. Therefore, farmers should carry a huge amount of fresh biomass to the agriculture fields at each time of application. It involves the transportation of

Azolla long distances and perishing the cultures. This reason leads to the poor adoption of *Azolla* by farmers [23]. *Azolla* is more prone to perish and cannot be stored for a long period [48]. Thus, quick application to the fields should be done to avoid deteriorating. Also, the tropical monsoon in Sri Lanka also destroys the *Azolla* cultivations, since heavy rainfall during this period may wash away the *Azolla* plants out of the pits.

Potential Strategies to Promote *Azolla* usage in Agricultural Field in Sri Lanka

Azolla is grown in various countries, including Sri Lanka, because of its vast majority of usage. However, the awareness on the cultivation and variety of benefits are lacking among farmers. Thus, local farmers should be given the necessary information about the technical know-how of growing *Azolla* and its usage in both crop cultivation and animal husbandry. Giving awareness and emphasizing its role as a sustainable and cost-effective source of feed for livestock and a natural biofertilizer for crop fields are some of the possible solutions to promote usage of *Azolla*. Cultivation of *Azolla* is an easy task because it can be grown in containers, either on a small or large scale. The most convenient size for the soil pits is 2m×1m×0.3m [49]. According to the Department of Animal Production and Health, Sri Lanka, the cost of production of 1 kg of *Azolla* can vary between Rs. 1.00-2.00 from one *Azolla* pit with the dimensions of 2 m×1 m×0.3 m within one production cycle of 8 months [49]. Availability of *Azolla* planting materials should be ensured, while conducting training programmes about the growing of *Azolla* [49]. Other than that, establishing demonstration farms, promoting research and development on *Azolla* cultivation and usages, providing financial incentives to farmers, integration into livestock systems, and information dissemination through technology are some other strategies to promote *Azolla* usage among farmer communities in Sri Lanka.

CONCLUSIONS

Against the background of economic challenges faced by Sri Lanka and the increasing concerns about synthetic fertilizers, *Azolla* emerges as a promising biofertilizer with multifaceted benefits to the agriculture sector. Its symbiotic relationship with *Anabaena azollae* makes it an efficient source of biological nitrogen, addressing the drawbacks associated with synthetic fertilizer alternatives. Beyond its role as a biofertilizer, versatility of *Azolla* extends to nutrient supplementation for animals, human consumption, phytoremediation, biofuel production, weed control, and even mosquito repellent properties. Numerous studies emphasize the efficacy of *Azolla*, positioning it as a viable and environmentally friendly alternative to synthetic fertilizers which pose environmental risks. With its rapid growth and sustainable harvesting, *Azolla* offers a reliable and sustainable solution for agricultural needs, during the economic crisis in Sri Lanka. Embracing *Azolla* as an agricultural resource not only addresses immediate concerns, but also aligns with the principles of environmental sustainability as green agriculture, marking it as a vital and sustainable asset for farmer communities in challenging times.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

AUTHORS' CONTRIBUTIONS

ISW: Conceptualized the study and wrote the manuscript. SRA: Conceptualized the study, wrote the manuscript and reviewed the manuscript. All authors read and approved the manuscript.

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