Harnessing *Azolla pinnata* for tropical feed security: nutritional potential, economic viability, and environmental impact

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Abstract. The anticipated global population growth to 9.7 billion by 2050 underscores the urgent need to identify sustainable protein sources to support future food systems. Traditional livestock production methods place a heavy burden on environmental resources, contributing significantly to climate change, water scarcity, and biodiversity loss. Consequently, the global community is exploring plant-based protein alternatives that are more ecologically viable and cost-effective. This study explores the nutritional and environmental potential of Azolla pinnata, an aquatic fern with remarkable protein content, as an alternative feed ingredient for poultry and aquaculture. Through biochemical analysis and feasibility studies, the research confirms Azolla pinnata's protein yield ranges between 20–30% in dry weight, comparable to soybean, making it a highly valuable substitute for imported feed ingredients like maize and soy meal. The study also discusses cultivation challenges, including growth inconsistency and environmental sensitivity, while proposing strategies such as controlled environment agriculture and integrated aquaponic systems for large-scale production. The findings indicate that Azolla could significantly reduce feed cost, enhance local agricultural resilience, and improve Malaysia's feed security, especially in reducing dependency on imported maize and soya. These results also align closely with the United Nations' Sustainable Development Goals (SDGs), particularly in addressing zero hunger, climate action, and sustainable agriculture.

1. Introduction

Forecasts estimate the world population will reach 9.7 billion by 2050, leading to immense pressure on global food systems [1]. Traditional animal-based proteins are increasingly scrutinized for their environmental impact, including high greenhouse gas emissions, water usage, and land degradation. These unsustainable trends in industrial livestock production

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not only contribute to ecological degradation but also compromise long-term food security. At the same time, urbanization, income growth, and changing dietary preferences are escalating global demand for meat and protein-rich diets. To accommodate this demand without further endangering ecosystems, it is crucial to develop alternative, sustainable protein sources that require fewer inputs and deliver substantial nutritional value.

In response, interest in plant-based alternatives has surged. Among these, one of the most underexplored but highly promising candidates is *Azolla pinnata*, a fast-growing aquatic fern native to Southeast Asia. Historically used as green manure in rice cultivation due to its nitrogen-fixing capability, Azolla is now garnering attention for its potential role in modern feed and food applications. *A.pinnata* harbours symbiotic cyanobacteria (*Anabaena azollae*) that enable it to fix atmospheric nitrogen, reducing the need for chemical fertilizers. It also boasts rapid biomass production and an impressive nutritional profile, including high protein content, essential amino acids, and micronutrients.

The potential for integrating Azolla into livestock and aquaculture feed systems offers a dual benefit: alleviating environmental pressure and improving the affordability and accessibility of protein sources. This study aims to evaluate the feasibility, nutritional value, and cultivation prospects of *A.pinnata* in the Malaysian context and beyond. Water fern, understood in everyday terms as *A.pinnata*, lives in warm and temperate regions. In Asia's heritage, it was once employed as a natural fertilizer, especially in rice fields. Its rapid growth and capacity to collect nitrogen through its collaboration with the cyanobacteria Anabaena azollae are important features of this fern [2]. Notably, animals can survive on this fern as a high-protein animal feed. Quite surprisingly, people might not be excluded either for a nutritional boost [3]. Overcoming protein shortage might just have this fern as a possibility, as its use shows promise.

A significant advantage exhibited by *A. pinnata* manifests in the form of its protein content. Precise dry weighing procedures depict a 20% to 30% protein yield under fluctuating growth scenarios [4]. Such values stand equivalent to those provided by established protein sources. Soybeans, for example, deliver a similar 36% protein ratio in their dry weight presence on the USDA data spectrum of 2019. Exploring further, Azolla pinnata is also considered rich in essential amino acids required for adequate human nutritional support systems. Vitamins and crucial minerals occupy its content list as well, adding considerable importance to its nutritional profile argument [5]. It displays an extraordinary capability for rapid biomass evolution within short growth spans. Doubling its presence in a mere three to ten days accentuates its potential for undergoing extensive production stages. The overall connection between the outlined benefits is hardly represented by the concrete scenarios mentioned, but the points stand, albeit somewhat disorganized in their interaction.

A. pinnata 's enchantment is a fervour concocted by the insatiable yearning for ecological virtue and equilibrium. When conventional cultivations go amiss with their avaricious demands - drenched arable lands, water like never-ending rivulets, impoverishing the earth even with fundamentals – *A. pinnata* develops in candid contrast. It finds protection in water systems - ponds, trenches. It does not contend with terrestrial agriculture. Barely craving for robust inputs, *A. pinnata* occupies the frontier of sustainable practices, even converting its origins to the dirtiest rivulets for maturation; thus, it balances the equation of water cleansing and nutrient recycling [6]. Nitrogen, vital but so destructively sourced for synthesizing fertilizers, becomes a product of boon when *A.pinnata* presents it on an atmospheric spread. Thus, its ecological performance report is thrust further to the constructive side [2].

2. Materials and methods

2.1 Sample collection and preparation

Samples of *A.pinnata* were collected from clean, freshwater sources located in Kedah, Malaysia. To ensure variability and representativeness, samples were gathered from three different aquatic sites with varying nutrient compositions. The collected biomass was thoroughly rinsed with distilled water to remove debris, sediments, and contaminants. After preliminary cleaning, the samples were divided into two groups: one group was air-dried under shaded conditions for 24 hours, while the second group underwent oven drying at 60°C until constant weight was achieved. Dried samples were then pulverized using a laboratory-grade grinder and stored in airtight containers at room temperature for subsequent analysis. Undried samples were also preserved in controlled cool environments for use in wet-based protein extraction studies.

2.2 Protein analysis (Kjeldahl method)

The protein content of the Azolla samples was determined using the established Kjeldahl method. Approximately 1.0 g of dried Azolla powder was digested with 15 mL of concentrated sulfuric acid in the presence of a catalytic mixture (copper sulphate and potassium sulphate). The digested material was then neutralized with sodium hydroxide, and the released ammonia was distilled and absorbed in boric acid solution. The solution was titrated using standardized hydrochloric acid. The nitrogen content was calculated using the titration values and then converted to crude protein using the factor 6.25.

The nitrogen content was determined using the formula:

$$\text{Total Nitrogen (\%)} = (V1-V2)\times N\times 1.4007 \,/\, \text{Sample Weight (g)}$$

where,

V1 is the volume of HCl used in the titration of the sample, V2 is the volume of HCl used in the titration of the blank, and N is the normality of HCl.

The nitrogen content was converted to crude protein content using the conversion factor 6.25:

$$\text{Crude Protein (\%)} = \text{Total Nitrogen (\%)} \times 6.25$$

The results was expressed as a percentage of crude protein.

2.3 Yield assessment and cultivation feasibility

Cultivation feasibility was assessed through a controlled experimental setup simulating open-pond conditions. Weekly yield measurements, temperature, humidity, nutrient concentrations, and water pH were recorded for a three-month cultivation period. Parameters such as doubling time, biomass productivity, and cost of production were evaluated. These findings were benchmarked against known values for conventional feed crops such as maize and soy.

3. Results and discussion

3.1 Protein content

The laboratory analysis revealed that wet Azolla samples yielded approximately 1.4g of protein per 100g, while dried samples showed significantly higher values of 23g/100g. This contrast underscores the importance of post-harvest processing in enhancing protein concentration. The protein content found in *A.pinnata* is comparable to that of soybean meal, a widely used protein source in animal feed. Notably, the amino acid analysis confirmed that Azolla contains substantial levels of lysine, methionine, and threonine—amino acids that are often limiting in many plant-based feed ingredients. These findings support the hypothesis

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that Azolla can be used to formulate balanced, protein-rich diets for livestock and aquaculture species.

Table 1. Protein Content Results

Sample	Protein content (g/100gm)
Wet *Azolla*	1.4
Dried *Azolla*	23

3.2 Cultivation challenges

Despite its nutritional advantages, several cultivation challenges were observed. Although Azolla exhibits rapid growth and can double in biomass within 3–5 days under optimal conditions, growth inconsistencies were noted after the third month of cultivation. Factors such as nutrient depletion, water temperature fluctuations, and fungal contamination led to browning and die-off. Moreover, maintaining water quality and preventing overcrowding are critical to sustaining biomass productivity. The study also found that yield losses were higher in stagnant water conditions, suggesting the need for dynamic water systems or aeration techniques. These limitations call for innovative cultivation systems such as floating beds, vertical ponds, or bioreactors to ensure consistent year-round output.

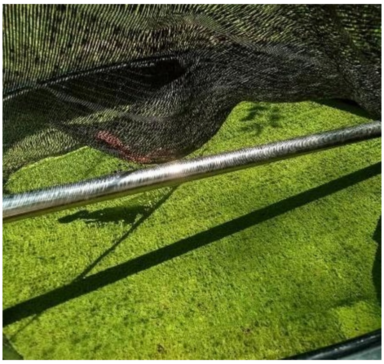

Fig. 1. 1st month indicated rapid *growth.*

Fig. 2. 2nd month growth still showing healthy Azolla population growth.

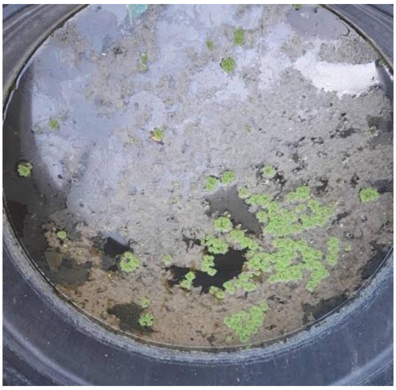

Fig. 3. by the end of 3rd month growth became inconsistent and the Azolla population began degrading and dying.

3.3 Economic feasibility

The cost analysis indicated that the operational expenditure for Azolla cultivation stood at approximately RM10 per kg of wet biomass. Market price surveys revealed that locally produced Azolla is being sold at RM30–50 per kg, offering a positive margin. However, the economic viability depends heavily on the scale of production and consistent output. Cost-saving strategies such as integrating Azolla farming with aquaculture (Azolla-fish polyculture systems) or reusing wastewater can improve financial returns. Governmental incentives, subsidies, or farmer cooperatives can further ease initial capital burdens and enhance adoption rates among smallholder farmers.

3.4 Plant feed consideration

Malaysia, being a Muslim-majority country, places significant emphasis on the halal integrity of the entire food supply chain, including animal feed. Concerns over the use of non-halal or contaminated feed ingredients have led to regulatory scrutiny. However, halal status is only granted for human consumables products thus enforcing halal control system on feed production is not relevant. In this context, using *A.pinnata* offers a compelling halal-compliant alternative, which is plant-based feed. As a purely plant-based, naturally occurring aquatic fern, its use in feed eliminates concerns regarding contamination with haram animal by-products. Moreover, incorporating Azolla into poultry and fish feed could boost consumer confidence and open export opportunities to other Muslim-majority countries with similar feed integrity concerns.

3.5 Environmental and social impact

Beyond its nutritional and economic value, Azolla cultivation offers multiple environmental benefits. Its ability to fix atmospheric nitrogen reduces dependency on synthetic fertilizers, thus mitigating eutrophication and groundwater contamination. Furthermore, Azolla farming has the potential to sequester carbon and regenerate aquatic ecosystems. On the social front, Azolla-based enterprises can stimulate rural economies by creating jobs in farming, processing, and distribution. Educational programs and training modules for farmers can promote awareness and empower communities to transition towards more sustainable practices.

4. Conclusion

A.pinnata presents a highly promising avenue for addressing global challenges in sustainable protein production, food security, and environmental conservation. With its superior protein content, rapid growth cycle, and minimal input requirements, Azolla stands out as a viable alternative to traditional animal feed ingredients. The study's findings highlight not only the biochemical feasibility of using Azolla in livestock and aquaculture diets but also emphasize the need for addressing cultivation and scalability constraints through technological innovations.

Malaysia's heavy reliance on imported feed commodities such as maize and soy presents economic and supply chain vulnerabilities. As the crisis worsened, local breeders and feedlot owners rushed to keep their businesses running and, without much choice, tried to find a feed replacement for the expensive marketed product. Several attempts have been made to develop alternative cattle feed sources. Azolla is regarded as the most cost-effective and efficient feed substitute, as well as a sustainable livestock feed. It has the potential to be a source of nitrogen and thus a feed additive for cattle [7,8]. This is where microalgae were identified as a potential replacement that might supply long-suffering breeders with cheaper feed choices while also lowering their operating feed costs. Incorporating Azolla into domestic feed production systems could reduce these dependencies while improving affordability and sustainability. While economic feasibility and environmental benefits are evident, realizing the full potential of Azolla requires a multisectoral approach involving policy support, public awareness, and scientific innovation. Future studies should focus on genetic enhancement, controlled-environment agriculture, protein extraction technology, and integration with circular agricultural systems. Azolla is regarded as the most cost-effective and efficient feed substitute, as well as a sustainable livestock feed. It has the potential to be a source of nitrogen and thus a feed additive for cattle [7,8]. This is where microalgae were identified as a potential replacement that might supply long-suffering breeders with cheaper feed choices while also lowering their operating feed costs.

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