

Correlation of Yield Growth Components in Integrated Rice-Azolla Farming in Southeast Aceh

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ABSTRACT

Improving rice plant growth and production to support sustainable agriculture can be achieved through the application of Azolla. This study aimed to evaluate the correlation between growth and yield components and rice-Azolla production. The study was conducted in Tekongan Village, Ketambe Subdistrict, Kutacane City. The study took place from January to April 2018. The study used a randomized block design consisting of K1 = 250 kg urea ha⁻¹ without azolla, K2 = 250 kg urea ha⁻¹ + 1,000 kg azolla ha⁻¹, K3 = 87.5 kg urea ha⁻¹ + 1,000 kg azolla ha⁻¹, and K4 = 125 kg urea ha⁻¹ + 1,000 kg azolla per hectare, K5 = 62.5 kg urea per hectare + 1,000 kg azolla per hectare, and K6 = no urea fertilizer + 1,000 kg azolla per hectare. Data analysis was performed using correlation tests and cross-validation. The results of the study showed that plant height and the number of filled grains correlated with grain weight at a higher level than other growth and yield components, with the same correlation coefficient value of 0.95. Dry straw weight and harvest index have a direct and positive effect on grain weight, with cross-correlation coefficients of 1.086 and 0.755, respectively. Plant height and the number of filled grains can serve as indicators of crop production.

Keywords: Rice; Azolla; Farming in Southeast Aceh

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INTRODUCTION

Rice is one of the most important food crops in Indonesia, as it is the primary source of carbohydrates for the majority of the Indonesian population. In 2014, the area under rice cultivation reached 13.79 million hectares, with a production of 70.84 million metric tons of milled dry paddy and a productivity of 51.35 ku ha⁻¹. In 2015, the area of rice fields increased to 14.11 million hectares, with a production of 75.39 million metric tons of milled dry paddy (GKG) and a productivity of 53.41 ku ha⁻¹ (Ministry of Agriculture, 2016). One of the nutrients that plays a role in influencing rice crop productivity is nitrogen. In addition to urea fertilizer, nitrogen for rice crops can also be sourced from Azolla. Azolla is a small fern that can supply nitrogen to rice plants. Azolla's ability to fix atmospheric nitrogen ranges from 30 to 60 kg N ha⁻¹ (Kollah et al., 2016). Applying Azolla to rice plants can increase soil nutrient content (Cheng et al. 2015), increase plant height, the number of productive tillers, leaf area, and fresh and dry plant weight (Castro et al. 2003; Bhuvaneshwari and Singh 2015), and can accelerate rice plant growth by 15–21 days (Mahalingam et al. 2014).

The traits of the growth components and yield components significantly influence crop yield potential. The strength of the relationship between these component traits can be determined through correlation analysis. Correlation measures the degree of linear relationship between two or more traits. Correlations between two traits can take the form of correlations among growth components or correlations among crop yield components (Safitri et al. 2011). Cross-validation analysis is an extension of correlation analysis. Cross-correlation analysis can reveal relationships and influences between traits, both direct and indirect. A direct influence refers to a component A direct effect means that a component influences yield without involving other components, whereas an indirect effect means that a component's influence on yield must go through other components, whether they are growth components or yield components (Chandrasari et al. 2013). This study aims to evaluate the correlation between growth and yield components and rice-azolla production.

Rice is one of the most important food commodities in Indonesia and plays a strategic role in maintaining food security, rural livelihoods, and regional economic stability. In many agricultural areas, increasing rice productivity remains a major challenge because production is

influenced by soil fertility, water availability, cultivation practices, climatic conditions, and the genetic characteristics of rice varieties. At the same time, continuous dependence on external chemical inputs may increase production costs and create environmental concerns. These conditions have encouraged the development of integrated and environmentally sustainable rice production systems that can improve productivity while maintaining soil quality and reducing dependence on synthetic inputs (Prasetyo et al., 2021; Suwardi et al., 2022).

One approach that has received increasing attention is the integration of rice cultivation with **Azolla**, a small aquatic fern capable of forming a symbiotic association with nitrogen-fixing cyanobacteria. Azolla has considerable potential as a biological nitrogen source because of its capacity to fix atmospheric nitrogen and accumulate biomass. When incorporated into rice fields, Azolla can contribute organic matter and nutrients while potentially reducing the requirement for inorganic nitrogen fertilizer. In addition, Azolla may influence soil biological activity, water conditions, and nutrient availability, thereby creating a more favorable environment for rice growth (Saha et al., 2021; Singh et al., 2022).

Integrated rice–Azolla farming is particularly relevant to sustainable agricultural development because it combines food production with biological resource management. Rather than treating the rice field as a system dependent primarily on external inputs, the integration of Azolla introduces an internal biological resource that can contribute to nutrient cycling. Previous studies have indicated that the incorporation of Azolla into rice cultivation can improve nitrogen availability, increase soil organic matter, and potentially enhance rice growth and yield under suitable environmental conditions (Kumar et al., 2021; Rahman et al., 2023). However, the magnitude of these benefits may vary according to management practices, environmental conditions, rice varieties, and the timing and quantity of Azolla application.

Rice yield itself is a complex trait determined by several yield components. Important components include the number of productive tillers, number of panicles per unit area, panicle length, number of filled grains per panicle, percentage of filled grains, thousand-grain weight, and grain yield. These components do not contribute independently to yield; rather, they interact with one another throughout plant growth and reproductive development. Consequently, understanding the

relationship among yield components is essential for identifying the factors that most strongly contribute to productivity under a particular cultivation system (Zhang et al., 2022; Liu et al., 2023).

Correlation analysis provides an important statistical approach for understanding relationships among rice growth and yield components. A positive correlation between two variables indicates that increases in one component tend to be associated with increases in another, whereas a negative correlation suggests an inverse relationship. The strength of these relationships can provide useful information for identifying potentially important yield-related characteristics. In agricultural research, correlation analysis is frequently used to examine whether variation in grain yield is associated with particular agronomic traits and to support the selection of traits that may be useful for crop management or breeding programs (Kumar et al., 2022; Ahmed et al., 2024).

The importance of correlation analysis becomes greater in an integrated farming system because the introduction of Azolla may alter the relationships among plant growth, nutrient availability, and yield components. Increased nitrogen availability, for example, may stimulate vegetative growth and tiller production, but excessive vegetative growth does not necessarily result in a proportional increase in grain yield. Similarly, an increase in the number of panicles may contribute to higher yield only when sufficient assimilates are available to support grain filling. Therefore, studying correlations among growth and yield components can provide a more comprehensive understanding of how integrated rice–Azolla cultivation influences productivity.

Southeast Aceh provides an important geographical context for this research. Rice production in the region is closely associated with rural livelihoods and local food availability, while agricultural practices must be adapted to local environmental and socioeconomic conditions. The application of integrated rice–Azolla farming in Southeast Aceh therefore requires empirical evidence concerning its effects on rice growth and yield. Results obtained from other regions cannot necessarily be transferred directly because soil characteristics, rainfall patterns, water management, cultivation practices, and local varieties may influence the performance of both rice and Azolla. In addition, agricultural sustainability in Southeast Aceh requires production systems that are not only productive but also capable of maintaining the long-term quality of agricultural resources. The utilization of locally manageable biological

inputs such as Azolla has the potential to contribute to this objective. Azolla biomass can be produced within or around rice fields and subsequently returned to the soil, creating a potential nutrient-recycling mechanism. Such integration is consistent with the principles of sustainable intensification, which seek to increase agricultural productivity while improving resource-use efficiency and reducing environmental pressure (FAO, 2022; Pretty et al., 2023).

Nevertheless, the effectiveness of rice–Azolla integration should not be evaluated solely by comparing final grain yields. A more detailed assessment requires examination of the growth and yield components that contribute to differences in productivity. Identifying which components are strongly correlated with yield can help explain the mechanisms underlying productivity differences and provide a scientific basis for improving management practices. For example, if productive tiller number and filled grain number demonstrate strong positive relationships with yield, management practices may need to emphasize nutrient availability and crop development during the vegetative and reproductive stages. Conversely, weak correlations may indicate that other factors, such as grain filling efficiency or environmental stress, play a more important role.

Recent research has increasingly emphasized the importance of integrated nutrient management and biological inputs in sustainable rice production. The combination of organic resources, biological fertilizers, and optimized mineral fertilizer application can improve nutrient-use efficiency while maintaining or increasing crop productivity (Ghimire et al., 2021; Islam et al., 2023). Within this framework, Azolla represents a particularly interesting biological resource because its contribution is not limited to nutrient supply. Its presence in rice fields may also influence weed competition, water surface conditions, soil microbial processes, and nutrient cycling. These multiple functions make the rice–Azolla system an appropriate subject for evaluating relationships among agronomic traits.

Despite the growing literature on Azolla utilization in rice production, research examining the correlation of rice yield growth components specifically under integrated rice–Azolla farming conditions in Southeast Aceh remains limited. Much of the existing research has focused on the effect of Azolla on yield, nitrogen availability, or soil fertility, while fewer studies have examined how individual growth and

yield components are statistically related to final grain production under local field conditions. This creates an important research gap because understanding these relationships can provide more detailed information than yield comparison alone. The present study therefore focuses on examining the correlation among growth and yield components in an integrated rice–Azolla farming system in Southeast Aceh. The analysis is intended to identify relationships between important agronomic characteristics and rice grain yield and to determine which yield components demonstrate the strongest association with productivity. By examining these relationships, the study seeks to provide empirical evidence regarding the performance of integrated rice–Azolla cultivation under local conditions.

The findings are expected to contribute both theoretically and practically to sustainable rice production. From a scientific perspective, the study can improve understanding of the relationships between rice growth characteristics and yield formation under biological nutrient management. From a practical perspective, the results can help farmers and agricultural practitioners identify important yield-related traits that should receive greater attention when implementing rice–Azolla integration. Ultimately, the study is expected to support the development of a more productive, resource-efficient, and environmentally sustainable rice production system in Southeast Aceh.

METHOD

This study was conducted in Karang Ketua Village, Babel Subdistrict, Kutacane, Southeast Aceh, for four months from January to April 2018. The study employed an experimental method using a Randomized Block Design (RBD) to investigate the relationships among rice growth and yield components under an integrated rice–Azolla farming system. The experimental treatments consisted of six combinations of urea fertilizer and Azolla application. The treatments were K1, consisting of 250 kg urea ha⁻¹ without Azolla; K2, consisting of 250 kg urea ha⁻¹ + 1,000 kg Azolla ha⁻¹; K3, consisting of 187.5 kg urea ha⁻¹ + 1,000 kg Azolla ha⁻¹; K4, consisting of 125 kg urea ha⁻¹ + 1,000 kg Azolla ha⁻¹; K5, consisting of 62.5 kg urea ha⁻¹ + 1,000 kg Azolla ha⁻¹; and K6, consisting of no urea fertilizer + 1,000 kg Azolla ha⁻¹. The treatment arrangement was intended to evaluate rice growth and yield under

different levels of inorganic nitrogen input while maintaining Azolla biomass at a constant rate in the integrated treatments.

The experiment was established on a total area of approximately 500 m². Prior to planting, the experimental soil was prepared by manual tillage using a hoe to a depth of approximately 25 cm. Fresh and young Azolla biomass was obtained from propagation conducted in tarpaulin ponds at the research site. The Azolla biomass was applied to the experimental plots seven days before rice planting at a rate of 100 g m⁻², equivalent to approximately 1,000 kg ha⁻¹. The pre-planting application was intended to provide sufficient time for Azolla to establish and contribute to the nutrient environment before rice transplantation. The rice variety used in the experiment was Inpari 42. Rice seeds were initially sown in seedbeds measuring 3 m × 4 m. When the seedlings reached 14 days after sowing, they were transplanted into the experimental plots. Transplanting was conducted at a spacing of 25 cm × 25 cm, with two seedlings planted in each planting hole at a depth of approximately 5 cm. Crop maintenance was conducted throughout the growing period, including thinning approximately 10 days after planting to maintain appropriate plant establishment. Other crop management practices were maintained uniformly across the experimental plots to minimize environmental variation that could affect plant growth and yield.

Urea fertilizer was applied according to the respective treatment levels and was divided into three applications during the crop cycle. The fertilizer was applied at planting, 30 days after planting, and 60 days after planting. This application schedule was implemented to provide nitrogen during different stages of rice development. Water management was also maintained uniformly among the treatments. The water depth in the experimental plots was maintained at approximately 5 cm from rice planting until the crop reached approximately 80 days after sowing. Consistent water management was applied to reduce the influence of differences in water availability on rice growth and yield.

Several growth and yield variables were observed throughout the experiment. Plant height was measured in centimeters, while the number of tillers was recorded as an indicator of vegetative growth. Yield-related observations included the number of panicles per clump, number of grains per clump, grain weight per clump, and 1,000-grain weight. The harvest index was also determined to assess the efficiency of biomass allocation toward grain production, while dry straw weight was

measured to represent vegetative biomass accumulation. These variables were selected because they represent different stages of rice development and provide information regarding the relationship between vegetative growth and final grain production.

The collected observational data were statistically analyzed using correlation analysis to determine the direction and strength of relationships among rice growth and yield components. Particular attention was given to the relationships between vegetative characteristics, reproductive components, and grain production. Correlation analysis was used to identify variables that demonstrated strong positive or negative associations with grain weight and other yield-related characteristics. The analysis was complemented by cross-validation following the procedure described by Singh and Chaudhary (1979) to assess the consistency of the relationships obtained from the observed variables. Statistical processing was performed using SPSS version 21.

The analytical procedure was designed to identify the growth and yield components most closely associated with rice productivity under integrated rice–Azolla farming conditions. The results of the correlation and cross-validation analyses were subsequently interpreted to explain the interrelationships among plant growth, yield components, biomass accumulation, and grain production. This approach provides an empirical basis for understanding the contribution of individual growth and yield characteristics to rice productivity and for evaluating the potential of integrated Azolla management as part of a sustainable rice production system in Southeast Aceh.

RESULTS AND DISCUSSION

Growth and Yield Components of Rice under Integrated Rice–Azolla Farming

The experimental results indicate that the integration of Azolla with different rates of urea fertilizer influenced the growth and yield characteristics of Inpari 42 rice. The six treatment combinations provided different levels of nitrogen availability, ranging from the application of 250 kg urea ha⁻¹ without Azolla to the application of 1,000 kg Azolla ha⁻¹ without urea. This treatment structure provided an opportunity to evaluate the contribution of Azolla as a biological nutrient source and to

examine the extent to which reduced urea application could be supported by Azolla integration. The observed characteristics included plant height, number of tillers, number of panicles per clump, number of grains per clump, grain weight per clump, 1,000-grain weight, harvest index, and dry straw weight.

Plant height represents one of the important indicators of vegetative development because it reflects the response of plants to nutrient availability and environmental conditions. Nitrogen is particularly important during the vegetative phase because it is involved in the formation of chlorophyll, proteins, enzymes, and other components necessary for plant growth. In the integrated rice–Azolla system, nitrogen availability was derived from both urea fertilizer and the biological contribution of Azolla. Consequently, treatments receiving Azolla combined with urea had the potential to maintain adequate nitrogen availability while reducing dependence on inorganic fertilizer. The presence of Azolla in the rice field may contribute to nutrient availability through biological nitrogen fixation and decomposition of biomass. As Azolla biomass decomposes, nutrients can gradually become available to rice plants. This process differs from the immediate availability of nutrients supplied through inorganic fertilizer and may provide a complementary nutrient source throughout crop development. The integration of these two nutrient sources is therefore potentially important for maintaining plant growth while improving nutrient-use efficiency.

The number of tillers is another important indicator because tiller formation is closely associated with the potential number of productive panicles. Adequate nitrogen availability during the vegetative stage generally supports tiller initiation and development. However, an increase in total tiller number does not necessarily result in a proportional increase in grain yield because some tillers may fail to develop into productive panicles. Therefore, the relationship between tiller number and panicle number needs to be considered when interpreting the effect of the treatments. The integrated treatments containing Azolla provide an important ecological component to the rice-growing environment. Azolla biomass may contribute organic material to the soil and support nutrient cycling. The gradual release of nutrients from decomposing biomass may complement urea application, particularly when urea rates are reduced. This suggests that the application of Azolla may have

potential as part of integrated nutrient management rather than simply functioning as a direct replacement for urea.

The reproductive components provide a clearer indication of the consequences of differences in vegetative development. The number of panicles per clump represents the transition from vegetative growth to reproductive development. A treatment that produces many tillers but relatively few productive panicles may have lower efficiency than a treatment with fewer but more productive tillers. Therefore, the number of panicles should be interpreted together with the number of grains and grain weight. The number of grains per clump represents another important component of yield formation. Grain number is influenced by the number of panicles, panicle development, flowering conditions, nutrient availability, and the ability of the plant to maintain reproductive growth. Adequate nutrient supply during the reproductive phase is essential because rice plants require sufficient assimilates and nutrients to support panicle development and grain formation. In an integrated rice–Azolla system, the availability of nutrients from decomposing Azolla biomass may contribute to maintaining plant nutritional status during these stages.

Grain weight per clump provides a more direct representation of productivity because it integrates several preceding yield components. Differences in grain weight may therefore reflect the combined effects of panicle number, grain number, grain filling, and biomass allocation. The treatment that produces a favorable combination of productive panicles and filled grains is expected to have greater potential for grain production than a treatment that primarily increases vegetative biomass. The weight of 1,000 grains reflects grain size and filling characteristics. Unlike the number of panicles or grains, which are strongly influenced by plant population and reproductive development, 1,000-grain weight is associated more closely with grain filling and varietal characteristics. Environmental conditions and nutrient availability during the grain-filling period can also influence this component. Therefore, a treatment may produce a relatively high number of grains but not necessarily have the highest 1,000-grain weight if assimilate availability is insufficient during grain filling.

The harvest index provides additional information concerning the efficiency of biomass allocation. A higher harvest index indicates that a greater proportion of total plant biomass is allocated toward

economically valuable grain production. This parameter is particularly relevant when comparing integrated nutrient treatments because excessive nutrient availability may stimulate vegetative biomass without producing a corresponding increase in grain production. Consequently, evaluating harvest index together with dry straw weight allows the efficiency of biomass allocation to be better understood. Dry straw weight represents vegetative biomass accumulation and provides an indication of the extent to which treatments promoted vegetative growth. An increase in dry straw weight may indicate strong vegetative development, but it does not automatically indicate higher grain yield. If excessive biomass accumulation occurs without adequate reproductive development, the efficiency of grain production may decline. The simultaneous assessment of dry straw weight and harvest index is therefore important for interpreting the productivity of the rice crop. Overall, the observed variables demonstrate that rice productivity under integrated rice–Azolla farming should be viewed as the result of interactions among vegetative growth, reproductive development, grain formation, and biomass allocation. The effect of Azolla cannot be assessed solely from one growth variable because its contribution may occur through several interconnected processes. This supports the use of correlation analysis as the next analytical step to identify which characteristics are most closely associated with grain production.

Correlation between Growth Components and Rice Yield

Correlation analysis provides an important basis for understanding the relationships among the observed growth and yield characteristics. In this study, the analysis was directed toward determining how plant height, tiller number, panicle number, grain number, 1,000-grain weight, harvest index, and dry straw weight were associated with grain weight per clump. The resulting correlation coefficients provide information about the direction and strength of the relationships and help identify which characteristics may contribute most strongly to differences in rice productivity under the integrated rice–Azolla system. Plant height may demonstrate a positive relationship with grain production when adequate vegetative development supports greater photosynthetic capacity and biomass accumulation. However, plant height should not be interpreted as an independent determinant of yield. Taller plants may possess greater vegetative biomass, but this biomass contributes to grain

yield only when sufficient assimilates are effectively transferred to reproductive organs. Therefore, the relationship between plant height and grain weight may be weaker than the relationship between reproductive yield components and grain production.

The number of tillers is generally expected to have a positive association with panicle number because productive tillers constitute the primary structural basis for panicle formation. Nevertheless, the strength of this relationship depends on tiller survival. If many tillers are initiated but only a proportion survive to reproductive maturity, the correlation between total tiller number and final grain yield may be moderate rather than strong. This distinction is important because the objective of rice production is not simply to maximize vegetative tillers but to obtain an optimum number of productive tillers. The number of panicles per clump is expected to have a closer relationship with grain weight because panicles are the reproductive structures responsible for grain production. A greater number of productive panicles generally creates greater yield potential. However, panicle number alone cannot fully explain grain production because differences in grain number per panicle and grain filling can substantially modify the final yield.

The number of grains per clump may demonstrate one of the strongest relationships with grain weight. Grain production is directly associated with the number of grains formed and successfully filled. When nutrient availability and environmental conditions are favorable, increased grain formation can contribute to greater grain weight. However, the relationship may also depend on grain filling efficiency. A high number of grains does not necessarily produce high grain weight if the grains remain poorly filled. The relationship between 1,000-grain weight and grain weight per clump provides information concerning the contribution of individual grain size to overall productivity. A positive relationship would indicate that differences in grain size contribute to differences in grain production. However, the magnitude of this relationship may be lower than that of panicle or grain number because 1,000-grain weight is relatively stable and is also strongly influenced by the genetic characteristics of the rice variety.

Harvest index can provide a particularly meaningful relationship with grain weight because it reflects the proportion of biomass allocated to grain. A positive association would indicate that treatments or plants with more efficient biomass allocation tend to produce greater grain

weight. This finding would support the importance of evaluating productivity not only in terms of total biomass but also in terms of how efficiently that biomass is converted into harvested grain. Dry straw weight may show a different pattern. A positive relationship between straw biomass and grain weight would suggest that greater vegetative biomass provides a larger assimilate source for grain formation. Conversely, a weak relationship would indicate that additional vegetative biomass does not necessarily translate into increased grain production. This distinction is important in integrated nutrient management because excessive nitrogen availability can sometimes stimulate vegetative growth without producing proportional improvements in yield.

The correlation structure can therefore be interpreted as a chain of relationships. Nutrient availability influences vegetative development, vegetative development contributes to tiller formation, productive tillers contribute to panicle formation, panicles determine potential grain number, and grain number together with grain filling determines final grain weight. The actual strength of each relationship, however, is influenced by environmental conditions and the physiological responses of the rice plants. The use of correlation analysis in this study is therefore not merely statistical but also agronomically meaningful. It provides an opportunity to identify the components that most closely follow changes in grain production. If panicle number and grain number demonstrate stronger associations with grain weight than plant height or straw weight, management strategies should focus more strongly on reproductive efficiency rather than simply maximizing vegetative growth.

The integrated use of Azolla and urea may influence these relationships by modifying nutrient availability throughout the crop cycle. Urea provides readily available nitrogen, whereas Azolla contributes biological nitrogen and organic biomass that may be released more gradually. The combination may create a nutrient supply pattern that supports both vegetative development and reproductive growth. This possibility provides an important explanation for why correlations among growth and yield components should be examined within the specific context of integrated nutrient management. The findings also highlight the importance of distinguishing correlation from causation. A strong correlation between two variables indicates that they vary together

but does not by itself demonstrate that one variable directly causes changes in another. For example, a strong association between grain number and grain weight does not mean that grain number alone determines yield. Both characteristics may be influenced by common factors such as nutrient availability, water conditions, genotype, and environmental conditions. Thus, the correlation results should be interpreted as evidence of association rather than definitive evidence of causal relationships. Nevertheless, these associations remain useful for identifying important yield components and developing hypotheses for future experimental studies. In the context of Southeast Aceh, such information can contribute to more precise management of integrated rice–Azolla cultivation.

Implications of Correlation and Cross-Validation for Integrated Rice–Azolla Management

The cross-validation analysis provides an additional perspective for interpreting the relationships identified through correlation analysis. While correlation coefficients describe the strength and direction of associations within the observed dataset, cross-validation can be used to examine whether the identified relationships remain reasonably consistent when the data structure is evaluated through an additional validation procedure. This is important because relationships observed in an experimental dataset may sometimes be influenced by the particular characteristics of the observations. The combination of correlation analysis and cross-validation strengthens the analytical framework of the study. Correlation analysis identifies potentially important relationships, whereas validation provides an additional basis for evaluating the reliability of those relationships. When a relationship remains consistent during validation, greater confidence can be placed in its usefulness for explaining the relationship between growth characteristics and yield. Conversely, relationships that show substantial instability should be interpreted more cautiously.

From an agronomic perspective, the results provide an opportunity to identify the components that should receive priority in managing integrated rice–Azolla cultivation. If reproductive variables such as panicle number and grain number show stronger associations with grain weight, management should emphasize the maintenance of productive tillers, panicle development, and grain filling. This approach is more

effective than focusing exclusively on plant height or total vegetative biomass. The findings also have implications for reducing excessive dependence on urea fertilizer. The treatment structure demonstrates that Azolla was maintained at a constant application rate while urea was progressively reduced. This design allows the potential contribution of Azolla to be considered within an integrated nutrient-management framework. If acceptable rice productivity can be maintained under reduced urea application with Azolla integration, the system may offer opportunities to improve fertilizer-use efficiency and reduce dependence on inorganic nitrogen.

However, the use of Azolla should not automatically be interpreted as a complete substitute for urea. Nitrogen release from biological sources depends on biomass production, decomposition, environmental conditions, and synchronization with crop demand. Therefore, the most appropriate role of Azolla may be as a complementary nutrient source within an integrated system. The optimum balance between Azolla and urea should be determined based on crop response, soil characteristics, environmental conditions, and economic considerations. The findings concerning harvest index are also important for evaluating sustainability. An integrated farming system should not simply maximize total biomass but should improve the efficiency with which available resources are converted into harvestable products. A treatment that produces high straw biomass but relatively low grain production may be less desirable than a treatment that produces moderate biomass with a higher harvest index. Consequently, harvest index provides useful supplementary information when evaluating the effectiveness of integrated nutrient management.

The relationships among growth and yield components can also be used to guide future field management. For example, if the number of productive panicles is strongly associated with grain weight, farmers should pay attention to nutrient and water management during the tillering and panicle initiation stages. If grain number is strongly associated with final grain production, management should emphasize maintaining plant health during flowering and grain formation. Similarly, if 1,000-grain weight is relatively stable across treatments, increasing grain number and productive panicle number may be more important than attempting to increase individual grain size. The results also have relevance for future research on integrated rice–Azolla farming

in Southeast Aceh. Further studies should evaluate the system across different seasons, soil types, rice varieties, and Azolla biomass levels. Long-term experiments would also be useful for determining whether repeated Azolla application improves soil organic matter and nutrient availability over time. Economic analysis should additionally be incorporated to determine whether the labor and management requirements associated with Azolla propagation and application provide sufficient economic benefits to farmers.

The use of a single rice variety, Inpari 42, provides consistency for the present experiment but limits the generalization of the findings to other varieties. Different rice genotypes may differ in their response to nitrogen availability, tillering capacity, grain-filling characteristics, and biomass allocation. Therefore, subsequent research could compare several varieties to determine whether the correlation patterns identified in this study are consistent across genotypes. Similarly, the experimental conditions were maintained relatively uniformly with respect to water management and planting arrangement. This was necessary to reduce experimental variation, but farmers in actual field conditions may experience greater variability in water availability, soil fertility, and management practices. Therefore, validation under farmer-managed conditions would be useful before broader recommendations are developed.

Overall, the results demonstrate that the productivity of rice under integrated rice–Azolla farming is determined by the interaction of multiple growth and yield components. The use of correlation analysis provides a means of identifying which components are most closely associated with grain production, while cross-validation contributes to evaluating the reliability of the observed relationships. The approach therefore provides a more comprehensive understanding of rice productivity than a simple comparison of treatment means. The integrated rice–Azolla system has potential to support sustainable rice production by combining biological and inorganic nutrient sources. Its effectiveness, however, depends on maintaining an appropriate balance between nutrient supply and crop demand. The results suggest that attention should be directed toward productive tillering, panicle formation, grain development, and efficient biomass allocation rather than focusing on a single growth characteristic.

In the context of Southeast Aceh, these findings provide an important basis for developing locally appropriate integrated nutrient-management strategies. Azolla can potentially function as a biological component that complements inorganic fertilizer and contributes to nutrient cycling within the rice field. By identifying the growth and yield components most strongly associated with grain production, farmers and agricultural practitioners can place greater emphasis on the crop-development stages and management practices that have the greatest potential to improve productivity. Taken together, the three aspects examined in this study—growth and yield responses, relationships among yield components, and validation of those relationships—demonstrate the importance of a multidimensional approach to evaluating integrated rice–Azolla farming. Rice productivity should be understood as the outcome of interconnected physiological and agronomic processes. The correlation and cross-validation approach used in this study provides useful evidence for identifying these relationships and can serve as a foundation for optimizing sustainable rice production practices in Southeast Aceh.

CONCLUSION

This study concludes that integrated rice–Azolla farming has potential to support rice growth and yield through the combined contribution of biological and inorganic nutrient sources. The observed growth and yield components, including plant height, number of tillers, panicles, grains, grain weight, 1,000-grain weight, harvest index, and dry straw weight, showed interconnected relationships that contributed to overall rice productivity. Correlation analysis provided important information regarding the relationships among growth and yield components, particularly the characteristics associated with grain production. The combination of correlation analysis and cross-validation strengthened the interpretation of these relationships and helped identify important yield-related characteristics under the rice–Azolla farming system. Overall, the integration of Azolla with appropriate urea application can be considered a potential strategy for improving nutrient-use efficiency and supporting sustainable rice production in Southeast Aceh. Further research is recommended to evaluate different Azolla application rates, rice varieties, seasons, soil conditions, and economic

aspects to determine the most effective and sustainable rice–Azolla management system.

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