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Relative Growth Rate and Net Assimilation Rate of Tomato Fertilized With Rice-Washing Water

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Abstract Rice-washing water enriched with coconut water has potential as a liquid organic fertilizer, but its effects on the physiological efficiency of tomato growth remain insufficiently characterized. This study evaluated relative growth rate (RGR) and net assimilation rate (NAR) under different fertilizer concentrations and application frequencies. The experiment was conducted from March to June 2023 in North Bengkulu, Indonesia. Plant dry mass and leaf area were measured at 2, 4, and 6 weeks after transplanting (WAT) to calculate RGR and NAR. The 1:10 dilution produced the highest RGR values, 0.81 and 0.65, during 2-4 and 4-6 WAT, respectively. The same dilution produced the highest NAR values of 0.0050 and 0.0028 g cm^{-2} day^{-1}. Application frequency did not independently affect either physiological indicator. Concentration and application frequency interacted for RGR during 4-6 WAT, with the strongest response at the 1:10 dilution applied two or three times. NAR declined across all treatments during the later interval, indicating reduced assimilation efficiency as plants aged. Thus, the 1:10 dilution provided the most favorable nutrient balance for tomato biomass accumulation and leaf-area efficiency. This manuscript reports physiological variables not presented in the previously published growth-and-yield article derived from the same experiment.

Keywords: *biomass accumulation; leaf area; liquid organic fertilizer; physiological growth; tomato*

INTRODUCTION

Tomato productivity at the farm level remains variable because of low soil fertility, imbalanced fertilization, and high dependence on inorganic fertilizers (Kementerian Pertanian RI, 2023; FAOSTAT, 2023). Tomato (*Solanum lycopersicum* L.) requires a balanced nutrient supply to sustain leaf-area development, photosynthesis, and biomass accumulation. Excessive fertilization does not necessarily increase growth because nutrient uptake is constrained by plant physiological requirements and growing-medium conditions. In intensive tomato production, improving nutrient-use efficiency is an important target for reducing nutrient losses while maintaining productivity (Liang et al., 2019). Tomato responses to organic fertilizers are context dependent and influenced by soil organic matter, total nitrogen, fertilizer type, and cropping system (Gao et al., 2023; Fan et al., 2023).

The use of rice-washing water as a liquid fertilizer represents a circular approach because this household waste stream still contains nutrients and organic compounds. It contains macronutrients such as nitrogen, phosphorus, and potassium, as well as micronutrients, vitamins, amino acids, and organic compounds that can support plant growth. Carbohydrates and organic matter in rice-washing water can also provide an energy source for soil microorganisms, thereby enhancing soil biological activity. When enriched with coconut water, which contains cytokinins, auxins, gibberellins, and various minerals, the quality of the liquid organic fertilizer may be improved, potentially promoting both vegetative and reproductive growth (Hasalsyah et al., 2024; Hanifa et al., 2022). Abba et al. (2021) reported that rice-washing water may contain nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and vitamins, although their concentrations vary with rice variety, water volume, and washing intensity. Chemical and microbiological characterization has also demonstrated its potential as a fertilizer and as a substrate for microorganisms that support soil health (Nabayi et al., 2021a).

Fermentation can alter the composition and nutrient availability of rice-washing-water fertilizer. Nabayi et al. (2021b) showed that fermentation increased populations of bacteria potentially beneficial to plants and altered nutrient concentrations. In this study, rice-washing water was fermented with coconut water, sugar, and EM-4. Coconut water was used as an enrichment material because it contains organic compounds and natural plant growth regulators that may promote cell division and tissue development.

The effects of fertilizers on plant growth are commonly assessed using plant height, leaf number, and yield. Although these indicators are important, they do not fully describe the efficiency with which plants accumulate biomass. Relative growth rate (RGR) describes the relative increase in biomass over a given interval, whereas net assimilation rate (NAR) describes the increase in dry matter per unit leaf area per unit time. These two indicators allow a more direct assessment of plant physiological responses to nutrient availability. This is important because nitrogen source and distribution strategy have been shown to affect tomato biomass accumulation, whereas poorly synchronized management can reduce nitrogen-use efficiency (Farneselli et al., 2018).

To date, information remains limited on how the combination of concentration and application frequency of rice-washing water liquid organic fertilizer (LOF) enriched with coconut water affects plant physiological growth, particularly RGR and NAR. The effects of concentration and application frequency of this LOF on tomato morphological growth and yield have previously been reported (Widodo et al., 2025). That article presented plant height, leaf number, stem diameter, days to flowering, fruit number, fruit diameter, and fruit weight. However, RGR and NAR data obtained from destructive measurements of biomass and leaf area were not presented or discussed in that publication. Consequently, the physiological component of the plant response remains insufficiently explained.

This manuscript presents a secondary physiological analysis of the same experiment and is restricted to RGR, NAR, and the interaction between concentration and application frequency for these two variables. No tables, figures, or previously published growth and yield results are reproduced. The manuscript examines how LOF concentration and application frequency influence the efficiency of biomass accumulation and leaf assimilation and identifies the concentration and application frequency of rice-washing-water fertilizer that are most effective in improving relative biomass accumulation and net assimilation efficiency in tomato.

MATERIALS AND METHODS

The study was conducted from March to June 2023 in Arga Makmur, North Bengkulu, Indonesia. The experimental design, materials, fertilizer, and crop management were derived from the same experiment as the growth-and-yield article published by Widodo et al. (2025). The previous article reported morphological and yield variables, whereas the present manuscript analyzes only the physiological RGR and NAR data that had not previously been reported and does not repeat variables already published. There is no duplication of tables, figures, principal results, or conclusions between the two articles.

Destructive measurements were conducted at 2, 4, and 6 WAT to determine plant dry weight and leaf area. Plants were removed from the growing medium, cleaned, and dried to constant weight before weighing. Leaf area was determined at each observation time. RGR was calculated from the change in the natural logarithm of dry weight over a given time interval, whereas NAR was calculated from the increase in dry weight corrected for changes in leaf area during the observation interval. Values were calculated for the 2-4 and 4-6 WAT periods using the following equations:

$$RGR\ (g\ day^{-1}) = (\ln W2 - \ln W1) / (t2 - t1)$$

$$NAR\ (g\ cm^{-2}\ day^{-1}) = [(W2 - W1) / (A2 - A1)] \times [(\ln W2 - \ln W1) / (t2 - t1)]$$

where:
W1 and W2 = plant dry weight at observations 1 and 2
t1 and t2 = plant age at observations 1 and 2
A1 and A2 = plant leaf area at observations 1 and 2

RGR and NAR data were analyzed by analysis of variance (ANOVA) according to the factorial design. When a factor or interaction had a significant effect, means were compared using Tukey's honestly significant difference (HSD) test at $\alpha = 5\%$. Interpretation focused on the effects of concentration and application frequency, changes between observation intervals, and the interaction between the two factors.

RESULTS AND DISCUSSION

Relative Growth Rate

LOF concentration affected RGR during both 2-4 and 4-6 WAT (Table 1). The 1:10 dilution produced the highest RGR in both periods, at 0.81 and 0.65 g day^{-1}, respectively. At 2-4 WAT, this value was higher than those obtained with the 1:5 and 1:15 dilutions, both of which produced 0.71 g day^{-1}. At 4-6 WAT, the 1:10 dilution also exceeded the 1:5 and 1:15 dilutions, which produced 0.43 and 0.48 g day^{-1}, respectively.

The difference of 0.10 between the 1:10 dilution and the other two dilutions at 2-4 WAT indicates that the plant response had already emerged during the early vegetative stage. At 4-6 WAT, the difference between 1:10 and 1:5 increased to 0.22, whereas the difference between 1:10 and 1:15 reached 0.17. The widening gap indicates that the physiological advantage of the 1:10 dilution was maintained as the plants progressed to the subsequent growth stage.

RGR integrates the outcomes of multiple physiological processes, including nutrient uptake, leaf-area development, photosynthesis, respiration, and dry-matter partitioning. Therefore, the higher RGR under the 1:10 dilution indicates that the plants converted available resources into biomass more efficiently. This response is consistent with evidence that nitrogen source and application method affect biomass accumulation in tomato (Farneselli et al., 2018).

The strongest response at 1:10 suggests the existence of an optimum concentration range. The more concentrated 1:5 solution did not increase relative biomass gain, whereas the 1:15 dilution may have supplied nutrients at concentrations below plant requirements. The composition of rice-washing water is highly variable; therefore, plant responses are determined by the nutrient balance after dilution and fermentation (Abba et al., 2021; Nabayi et al., 2021a).

The absence of a linear dose-response relationship is agronomically important. If the response were determined solely by the amount of dissolved material, the 1:5 dilution should have produced the highest RGR. The opposite result suggests that nutrient balance, solution osmotic pressure, and mineralization rate may be more influential than total concentration. Several studies have shown that the benefits of organic fertilizer for tomato depend on soil properties, the type of organic material, and the level of nitrogen availability (Gao et al., 2023; Fan et al., 2023).

Rice-washing water is a liquid organic material with a non-uniform composition. Abba et al. (2021) and Nabayi et al. (2021a) emphasized that nutrient content is influenced by the raw material and washing process. Following fermentation, shifts in microbial populations and transformation of organic compounds may also alter the forms of nutrients available to plants (Nabayi et al., 2021b). Therefore, the optimum dilution should be determined from plant responses rather than fertilizer volume alone.

Application frequency did not independently affect RGR. RGR values ranged from 0.73 to 0.76 at 2-4 WAT and from 0.45 to 0.56 at 4-6 WAT. These results indicate that two applications provided conditions comparable to those achieved with three or four applications. Increasing application frequency does not necessarily enhance growth when nutrients from previous applications remain available or when the physiological requirements of the plants have already been met.

The non-significant main effect of application frequency also indicates that the application schedule during 1-4 WAT was not a major constraint on growth. Two applications may have supplied sufficient nutrients during the early growth stage, whereas additional applications did not necessarily improve growth because nutrient availability and plant demand are not always synchronized. Research on tomato has shown that fertilizer dose and timing should be matched to the growth stage to improve biomass accumulation and nitrogen-use efficiency (Farneselli et al., 2018).

However, the absence of a significant main effect of frequency does not mean that application timing is entirely unimportant. The interaction at 4-6 WAT indicates that application frequency elicited a response only when combined with a particular concentration. Thus, the effect of application frequency should be interpreted in relation to LOF concentration and plant developmental stage.

RGR declined in all treatments from 2-4 to 4-6 WAT. This decline indicates that relative biomass accumulation was faster during the earlier growth stage. As plants age, increased maintenance respiration, a higher proportion of older tissues, and a shift in photoassimilate allocation toward reproductive organs reduce relative biomass gain.

Quantitatively, the reduction in RGR among the concentration treatments ranged from 0.16 to 0.28 between the two intervals. The smallest decline occurred at 1:10; thus, this treatment not only produced the highest RGR but also maintained a higher growth rate during the subsequent interval. This finding suggests that the nutrient balance at 1:10 may delay the decline in relative growth efficiency.

Table 1. Relative growth rate of tomato plants under different concentrations and application frequencies of rice-washing-water LOF at 2-4 and 4-6 WAT

Treatment	RGR g day^{-1}	
	2-4	4-6
Concentration		
1:5	0.71 b	0.43 b
1:10	0.81 a	0.65 a
1:15	0.71 b	0.48 b
Application frequency		
Two applications	0.76	0.56
Three applications	0.75	0.52
Four applications	0.73	0.45
Interaction	ns	*

Note: Means followed by different letters within the same column differ significantly according to Tukey's HSD test at α = 5%; WAT = weeks after transplanting; ns = not significant; * = significant.

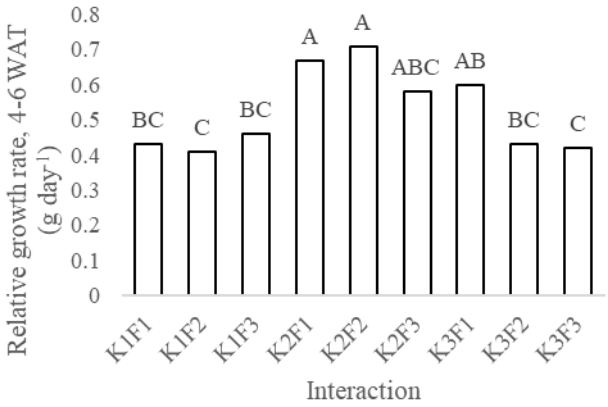

Figure 1. Interaction between concentration and application frequency of rice-washing-water LOF for relative growth rate at 4-6 WAT; WAT = weeks after transplanting.

The interaction at 4-6 WAT indicates that the response to application frequency depended on solution concentration (Figure 1). The 1:10 dilution applied two or three times produced the highest RGR, whereas increasing the frequency to four applications did not improve the response. At concentrations of 1:5 and 1:15, changes in application frequency also produced non-linear patterns. Thus, the optimum concentration was more important than simply increasing the number of applications.

The interaction pattern shows that four applications did not produce the highest response at the 1:10 dilution. This may occur when additional solution no longer increases effective nutrient availability or when nutrient balance in the root zone changes. These findings support the principle that the optimum dose of liquid organic fertilizer should be determined empirically; in a study of starfruit-waste LOF, an intermediate dose of 35 mL polybag^{-1} was more effective than lower or higher doses in supporting tomato production (Sumiasih et al., 2023).

Net Assimilation Rate

LOF concentration affected NAR during both observation periods (Table 2). At 2-4 WAT, the 1:10 dilution produced the highest NAR, 0.0050 g cm^{-2} day^{-1}, and differed significantly from 1:15 but not from 1:5. At 4-6 WAT, the 1:10 dilution produced an NAR of 0.0028 g cm^{-2} day^{-1}, which was higher than the values for 1:5 and 1:15. During 2-4 WAT, NAR at 1:10 was 19.0% higher than at 1:5 and 42.9% higher than at 1:15. During 4-6 WAT, these advantages increased to 64.7% and 55.6%, respectively. These relative differences indicate that the effect of concentration became more pronounced as the plants developed and internal competition for light and assimilates increased.

The high NAR at the 1:10 dilution indicates that biomass accumulation was more efficient relative to the available leaf area. Nitrogen supports chlorophyll formation and photosynthetic enzymes, whereas potassium contributes to stomatal regulation and assimilate translocation. However, these benefits depend on nutrient balance; therefore, a more concentrated solution does not necessarily increase assimilation efficiency. Other studies have shown that the effects of organic fertilizer on tomato performance are determined by the balance of nutrient supply and soil conditions rather than by the amount of organic material alone (Wu et al., 2022; Gao et al., 2023).

NAR is a measure of the efficiency of leaf area in producing additional dry matter. High NAR can occur when leaves are photosynthetically active, carbon losses through respiration are relatively low, and assimilates are rapidly utilized for growth. Therefore, the superior NAR at 1:10 reinforces the RGR results and indicates that the increase in biomass resulted not only from leaf expansion but also from greater physiological productivity per unit leaf area.

Organic fertilizers can support these processes through gradual nutrient release and improvement of the growing medium. Adekiya et al. (2019) showed that organic materials can improve porosity, soil organic matter, nutrient content, growth, and tomato yield. In Ultisol, organic fertilizer enriched with Trichoderma sp. also increased shoot dry weight and yield components of tomato, indicating improvements in medium function and nutrient uptake (Ikawati et al., 2022).

Application frequency and the concentration × frequency interaction did not affect NAR. NAR values ranged from 0.0041 to 0.0045 g cm^{-2} day^{-1} at 2-4 WAT and from 0.0020 to 0.0023 g cm^{-2} day^{-1} at 4-6 WAT. The absence of an interaction indicates that the effect of concentration on NAR was relatively consistent across application frequencies. Based on application frequency, the numerically highest NAR during 4-6 WAT occurred with three applications (0.0023 g cm^{-2} day^{-1}), but this value did not differ significantly from those obtained with two or four applications. Therefore, the numerical difference is insufficient to justify recommending a higher application frequency. This result is consistent with evidence that the effectiveness of organic fertilizer depends on an optimum dose and suitability to the cropping conditions; weekly application is not always superior when plant requirements have already been met (Sumiasih et al., 2023).

NAR declined from 2-4 to 4-6 WAT in all treatments. This decline may be associated with leaf aging, increased mutual shading among leaves, higher tissue respiration, and a shift in photoassimilate allocation toward reproductive organs. Therefore, an increase in leaf area at later growth stages does not necessarily result in a proportional increase in dry matter.

The magnitude of the decline in NAR varied among treatments. At the 1:10 dilution, NAR decreased by 44%, whereas the declines at 1:5 and 1:15 were approximately 59.5% and 48.6%, respectively. Although all treatments showed a decline, the 1:10 dilution maintained the highest absolute value. This pattern is consistent with the smaller decline in RGR observed at the same concentration. The parallel trends in RGR and NAR indicate that leaf assimilation efficiency contributed to relative biomass accumulation. As NAR declined, the amount of additional dry matter produced per unit leaf area also decreased, leading to a reduction in RGR. The agreement between these two indicators strengthens the conclusion that the 1:10 dilution provided the most favorable physiological conditions among the treatments tested.

Table 2. Net assimilation rate of tomato plants under different concentrations and application frequencies of rice-washing-water LOF at 2-4 and 4-6 WAT

Treatment	NAR g cm^{-2} day^{-1}	
	2-4	4-6
Concentration		
1:5	0.0042 ab	0.0017 b
1:10	0.0050 a	0.0028 a
1:15	0.0035 b	0.0018 b
Application frequency		
Two applications	0.0045	0.0020
Three applications	0.0044	0.0023
Four applications	0.0041	0.0020
Interaction	ns	ns

Note: Means followed by different letters within the same column differ significantly according to Tukey's HSD test at α = 5%; NAR unit = g cm^{-2} day^{-1}; WAT = weeks after transplanting; ns = not significant.

The consistent RGR and NAR responses at the 1:10 dilution indicate that this treatment not only accelerated biomass accumulation but also improved dry-matter production efficiency per unit leaf area. This result is consistent with global syntheses showing that organic fertilizers can improve tomato performance, although the magnitude of the response is strongly influenced by fertilizer type, soil conditions, and combination with mineral fertilizers (Gao et al., 2023; Yang et al., 2023).

These results show that the evaluation of liquid fertilizers should not rely solely on plant height or leaf number. Treatments may produce similar morphology but differ in physiological efficiency. Research on tomato in Indonesia has also shown that organic materials enriched with microorganisms can increase shoot dry weight and yield, underscoring the importance of biomass measurements in evaluating fertilizer effectiveness (Ikawati et al., 2022).

Overall, the results indicate that the 1:10 LOF concentration was the best treatment for improving plant physiological efficiency, as demonstrated by the highest RGR and NAR values, whereas the combination of 1:15 with three applications produced the highest number of fruits. Meanwhile, plant height, leaf number, and fruit weight did not differ significantly among treatments. These findings indicate that rice-washing-water LOF enriched with coconut water was more effective in improving physiological growth efficiency and plant productivity than in altering morphological growth alone. Therefore, determining the appropriate concentration and application frequency is important for optimizing sustainable tomato cultivation using liquid organic fertilizer.

Interpretation of this study is limited by the absence of analyses of LOF nutrient composition, plant tissue nutrients, chlorophyll, and direct photosynthetic rate. Therefore, the mechanisms underlying the increases in RGR and NAR at the 1:10 dilution require confirmation through nutrient analysis and gas-exchange measurements. Future studies should compare organic fertilizer alone with combined organic-inorganic fertilization, because global evidence indicates that the combination more consistently increases plant dry weight and yield than organic fertilizer alone (Yang et al., 2023).

Another limitation is that RGR and NAR were calculated for only two intervals; therefore, more detailed dynamics before 2 WAT and after 6 WAT cannot be described. More frequent measurements would help determine when the response to LOF begins and when assimilation efficiency declines most sharply. Such analyses are also important for aligning fertilizer application timing with the growth stages at which plant nutrient demand is greatest.

CONCLUSIONS

The 1:10 dilution of rice-washing-water LOF produced the highest RGR and NAR during both 2-4 and 4-6 WAT. Application frequency did not independently affect RGR or NAR. Concentration and application frequency interacted for RGR during 4-6 WAT, with the highest response at the 1:10 dilution applied two or three times, whereas no interaction occurred for NAR. Both RGR and NAR declined during the 4-6 WAT interval, indicating lower relative biomass gain and net assimilation efficiency as plants aged. The 1:10 dilution was the most suitable concentration

for improving the physiological growth efficiency of tomato, within the limitation that the analysis focused on physiological indicators and did not include morphological variables.

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