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CIRCULAR NUTRIENT INPUTS FOR RED CHILI: EGGSHELL POWDER AND RICE-WASH WATER

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ABSTRACT

Household food residues are increasingly considered low-cost nutrient resources, yet their effectiveness depends on nutrient form, release rate, and crop demand. This study evaluated the individual and combined effects of eggshell powder and fresh rice-wash water on red chili (Capsicum annuum L.) growth, phenology, and yield. A 3 × 3 factorial randomized block design with three replications was conducted in Medan, Indonesia, from April to July 2026. Eggshell powder was applied at 0, 10, and 20 g plant-1, while rice-wash water was applied at 0, 250, and 350 mL plant-1. Data were analyzed by ANOVA followed by Duncan's multiple range test at 5% when significant. Eggshell powder did not significantly affect any measured trait. Rice-wash water significantly increased stem diameter at 3 weeks after planting (2.60-2.65 mm versus 2.40 mm in the control), advanced flowering to 34.89 days at 350 mL plant-1 compared with 37.78 days in the control, and shortened harvest age to 68.00 days compared with 69.33 days. However, these effects did not persist into significant differences in fruit number or fruit weight. No eggshell × rice-wash-water interaction was detected. The findings reveal a temporally specific response: readily available nutrients from fresh rice-wash water influenced early growth and crop phenology, whereas untreated eggshell CaCO3 was apparently too slowly available to generate a yield response within one crop cycle. Synchronizing residue processing and nutrient release may therefore be more important than simply combining household-waste inputs.

Keywords: Capsicum annuum; circular nutrients; eggshell waste; rice-wash water; organic amendment.

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INTRODUCTION

Red chili pepper (Capsicum annuum L.) is a high-value horticultural crop whose productivity is closely linked to balanced nutrient supply. In intensive vegetable systems, fertilizer management must support rapid vegetative development, flowering, fruit set, and repeated harvests while avoiding excessive input costs and nutrient losses. Studies on red chili have repeatedly shown that changing fertilizer source, concentration, or nutrient balance can alter growth and yield, but responses are strongly conditioned by the fertility of the rooting medium and by whether nutrients are available when plant demand is highest (Ananto & Alatas, 2022; Rismayanti et al., 2024; Setiyawan & Octavia, 2025; Yuliani et al., 2024). Similar factorial crop experiments published in Algebra have demonstrated that growth regulators and soil-related inputs can affect different response variables at different growth stages rather than producing a uniform response throughout the crop cycle (Azhari et al., 2025; Hasibuan et al., 2024).

The search for low-cost nutrient sources is increasingly connected with circular agriculture. Organic amendments can recycle nutrients and carbon that would otherwise enter waste streams, potentially improving soil properties and reducing dependence on conventional inputs. Their agronomic value, however, is not determined by the label "organic" alone. Nutrient concentration, solubility, decomposition, microbial transformation, particle size, soil pH, and the timing of application determine whether an amendment can release nutrients at a rate that matches crop demand. Reviews of organic fertilization therefore emphasize both its sustainability potential and the need to manage nutrient availability, because slowly mineralizing or compositionally unbalanced materials may improve soil quality without necessarily producing an immediate yield response (Gamage et al., 2023; Liu et al., 2024).

Eggshell waste is a particularly abundant household and food-service residue. It is composed predominantly of calcium carbonate and can function as a calcium source and liming material. Recent evidence shows that ground eggshell can raise soil pH and improve phosphorus availability, but the response depends on soil properties, dose, grinding, and incubation time (Sebonela et al., 2024). Eggshell-based fertilizers have also been explored in liquid or processed forms, with positive growth responses reported in tomato when the material is converted into a more readily available formulation (Abudrahman et al., 2026). At the soil level, eggshell amendments have been reported to improve chemical properties, supporting their potential as a recycled soil input (Sanuriza & Risfianty, 2020). A recent review further frames eggshell valorization as a circular-bioeconomy strategy while highlighting processing and release kinetics as critical for agronomic performance (Sainz-Hernández et al., 2026). These findings imply that raw powder incorporated shortly before or during a crop cycle may behave differently from incubated, acidified, fermented, or liquid eggshell products.

Rice-wash water is another household residue with agricultural potential. Chemical characterization shows that washed rice water can contain dissolved nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and organic compounds, although concentrations vary substantially with washing intensity, water-to-rice ratio, and fermentation period (Nabayi et al., 2021). Consecutive application studies show that both unfermented and fermented rice-wash water can modify plant growth, soil nutrient status, and microbial populations, but soil texture and repeated application influence the magnitude of the response (Nabayi et al., 2022). Fermentation may increase nutrient availability, and combining fermented rice-wash water with mineral fertilizer can produce stronger nutrient uptake and biomass responses than either dilute organic input or mineral fertilizer alone (Nabayi et al., 2023). Field and pot studies likewise report that the effect of rice-wash water is sensitive to concentration, fermentation, application frequency, and companion nutrients (Kustiawan et al., 2024; Pega et al., 2025; Syafi'i et al., 2025; Widodo et al., 2025).

The simultaneous use of eggshell and rice-wash residues is appealing because the two materials differ in nutrient composition and expected release behavior. A previous study using rice-wash water and eggshell-derived liquid fertilizer on mustard greens supported the feasibility of recycling both household residues, but crop, formulation, and treatment conditions differ from those of red chili (Rombe & Pakasi, 2021). Other rice-wash-water studies have combined it with monosodium glutamate or additional nutrient sources, again suggesting that the surrounding nutrient context can determine whether the response is sustained (Rikhma Sari et al., 2023). There remains a practical gap concerning the direct factorial combination of dry, untreated eggshell powder with fresh, unfermented first-wash rice water in red chili. The key question is not only whether either residue is beneficial, but whether their different nutrient-release patterns generate a synergistic response within a single production cycle.

Accordingly, this study aimed to determine the main effects of eggshell powder and rice-wash water, and their interaction, on red chili plant height, stem diameter, flowering age, harvest age, fruit number, fruit weight per sample plant, and fruit weight per plot. The working hypothesis was that increasing residue inputs would improve growth and yield and that their combination would produce an interaction. The novelty of the study lies in testing two minimally processed household residues in a factorial design and interpreting the response across time. This approach distinguishes an early or phenological response from a true yield response, which is important when evaluating household-waste inputs as practical nutrient-management tools.

RESEARCH METHODS

The experiment was conducted from April to July 2026 at Jalan Melintang No. 5, Dwi Kora, Medan Helvetia, North Sumatra, Indonesia. Red chili plants were grown individually in 35 × 35 cm polybags. The growing medium consisted of topsoil and well-decomposed manure mixed at a 2:1 ratio. The medium was placed in the polybags, moistened, and allowed to stabilize for approximately seven days before transplanting. Seedlings were raised until 14-21 days old or until they had approximately four to five true leaves, after which uniform and healthy plants were transplanted at one seedling per polybag.

A factorial randomized block design was used with two treatment factors. The first factor was eggshell powder (T): T0 = 0 g plant-1, T1 = 10 g plant-1, and T2 = 20 g plant-1. The second factor was fresh rice-wash water (A): A0 = 0 mL plant-1, A1 = 250 mL plant-1, and A2 = 350 mL plant-1. The 3 × 3 arrangement generated nine treatment combinations and was repeated in three blocks, resulting in 27 experimental plots. Each plot contained four plants, of which three were designated as sample plants. Thus, the experiment contained 108 plants in total and 81 sample plants. Polybags were spaced approximately 10 cm apart, plots 40 cm apart, and blocks 70 cm apart; each plot occupied approximately 80 × 80 cm.

Eggshell powder was prepared from chicken eggshells that were washed, sun-dried for 3-5 days, ground, and sieved to obtain a fine powder. It was applied once at 7 days after transplanting by distributing the assigned dose around the rooting zone approximately 5-10 cm from the stem, lightly mixing it into the surface medium, and watering afterward. Rice-wash water was collected from the first washing of rice using clean water, filtered, and used fresh without fermentation. It was applied beginning at 2 weeks after planting by pouring the assigned volume around the root zone at approximately the same radial distance from the stem. These preparation details are analytically important because nutrient availability from unfermented rice-wash water and untreated eggshell powder is expected to differ from fermented or chemically processed products documented in the literature (Nabayi et al., 2021; Sainz-Hernández et al., 2026).

Routine crop management included watering according to environmental conditions, weed control, replacement of dead seedlings when necessary, and pest or disease management when required. Plant height was measured from the medium surface to the highest growing point at 3, 4, 5, 6, and 7 weeks after planting (WAP). Stem diameter was measured approximately 3 cm above the medium surface with a caliper at the same observation ages. Flowering age was recorded as days after transplanting until the first fully opened flower, and harvest age as days after transplanting until fruit reached the defined harvest maturity, characterized by uniform red color. Fruit number per sample plant, fruit weight per sample plant, and total fruit weight per plot were recorded from harvested fruit.

Data were subjected to analysis of variance (ANOVA) for a factorial randomized block design using the model $Y_{ijk} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk}$, where ρ_i represents block effects, α_j the eggshell-powder effect, β_k the rice-wash-water effect, and $(\alpha\beta)_{jk}$ their interaction. When a treatment effect was significant, means were separated using Duncan's multiple range test (DMRT) at the 5% level (Duncan, 1955). Results are reported as treatment means. Because the source dataset reports significance decisions rather than complete p-values for every response, the article retains the original significance classification and does not infer unreported p-values.

RESULTS AND DISCUSSION

Overall factorial response

The factorial analysis revealed a selective rather than generalized response to the two household-waste inputs. Eggshell powder had no significant main effect on any measured variable, and the eggshell × rice-wash-water interaction was not significant for any variable. Rice-wash water showed significant effects only on stem diameter at 3 WAP, flowering age, and harvest age. Plant

height at 3-7 WAP, stem diameter at 4-7 WAP, fruit number, fruit weight per sample plant, and fruit weight per plot were not significantly affected by rice-wash water. This pattern is summarized in Table 1 and indicates that statistical effects were concentrated in early vegetative growth and phenological timing rather than final productivity.

Table 1. Summary of factorial treatment effects on red chili responses

Response	Eggshell powder	Rice-wash water	Interaction
Plant height, 3-7 WAP	ns	ns	ns
Stem diameter, 3 WAP	ns	*	ns
Stem diameter, 4-7 WAP	ns	ns	ns
Flowering age	ns	*	ns
Harvest age	ns	*	ns
Fruit number per sample	ns	ns	ns
Fruit weight per sample	ns	ns	ns
Fruit weight per plot	ns	ns	ns

*Note: * = significant at the 5% level; ns = not significant. WAP = weeks after planting.*

Vegetative growth response

Plant height increased normally over time in all treatments, from approximately 20 cm at 3 WAP to 47-50 cm at 7 WAP when main-effect means were considered. However, neither eggshell powder nor rice-wash water produced significant differences in plant height at any observation age. At 7 WAP, the eggshell means were 49.96, 49.15, and 46.96 cm for T0, T1, and T2, respectively, while the rice-wash-water means were 50.52, 46.70, and 48.85 cm for A0, A1, and A2. These numerical differences should therefore be treated as descriptive variation rather than evidence of treatment superiority. Similar cautions are important in fertilizer experiments because organic inputs can produce visible mean differences that are not statistically distinguishable under experimental variability (Ananto & Alatas, 2022; Setiyawan & Octavia, 2025).

Stem diameter showed the clearest early response. At 3 WAP, A1 and A2 produced mean diameters of 2.60 and 2.65 mm, respectively, and both were significantly greater than A0 at 2.40 mm. This response disappeared from 4 through 7 WAP: at 7 WAP, means were 6.38, 6.19, and 6.30 mm for A0, A1, and A2. Eggshell powder remained non-significant throughout, although T1 had the highest numerical diameter at several observation ages (Table 2). The transient nature of the rice-wash-water effect is consistent with the concept that fresh washed rice water contains soluble nutrients but in concentrations that vary with preparation and may be insufficient to sustain a long crop cycle without repeated or complementary nutrient supply (Nabayi et al., 2021, 2022). Kustiawan et al. (2024) observed stronger responses when rice-wash water was combined with organic NPK, underscoring the role of nutrient complementarity. Widodo et al. (2025) likewise reported concentration- and frequency-dependent effects on tomato stem diameter and flowering when rice-wash-water fertilizer was enriched and repeatedly applied.

Table 2. Main-effect means for selected vegetative growth variables

Treatment	Height 3 WAP (cm)	Height 7 WAP (cm)	Stem 3 WAP (mm)	Stem 7 WAP (mm)
T0: 0 g eggshell	19.83	49.96	2.50	6.31
T1: 10 g eggshell	21.31	49.15	2.63	6.43
T2: 20 g eggshell	20.65	46.96	2.52	6.12
A0: 0 mL rice-wash	20.22	50.52	2.40 b	6.38
A1: 250 mL rice-wash	20.48	46.70	2.60 a	6.19
A2: 350 mL rice-wash	21.09	48.85	2.65 a	6.30

Note: Within the rice-wash-water factor at 3 WAP, means followed by different letters differ by DMRT at 5%. Other displayed comparisons were not significant.

The absence of an eggshell effect is biologically plausible under the preparation method used. Eggshell is primarily a CaCO3-rich material; its agronomic function is often expressed through liming, calcium supply, and changes in phosphorus availability rather than through rapid delivery of nitrogen, phosphorus, and potassium in the proportions required for vigorous chili growth. Sebonela et al. (2024) showed that ground eggshell can raise soil pH, but their work included soil incubation and demonstrated that response is mediated by soil characteristics and reaction time. Sanuriza and Risfianty (2020) also documented improvements in soil chemical properties after eggshell application. In contrast, the present powder was applied after transplanting and therefore had limited time to react within the root medium. Recent eggshell research further suggests that processed or liquid formulations can produce faster plant responses than untreated shell powder (Abudrahman et al., 2026; Sainz-Hernández et al., 2026). The manure-containing medium used here may also have

provided sufficient background fertility to reduce the marginal response to additional calcium-rich material.

Flowering and harvest timing

Rice-wash water significantly accelerated the transition to reproductive growth. Plants receiving 350 mL plant-1 (A2) flowered at 34.89 days, about 2.89 days earlier than the control at 37.78 days; A1 was intermediate at 36.22 days. The same treatment also shortened harvest age to 68.00 days compared with 69.33 days for both A0 and A1. Eggshell powder did not significantly affect flowering or harvest age. These findings are agronomically meaningful even though the absolute differences are modest, because earlier flowering and harvest can affect crop scheduling and market timing. However, phenological acceleration should not automatically be interpreted as improved productivity.

The phenological effect is consistent with studies showing that rice-wash-water responses depend strongly on formulation. Pega et al. (2025) reported favorable red-chili growth and yield responses to fermented rice-wash water in combination with NPK, with 450 mL plant-1 performing well for several variables. Syafi'i et al. (2025) found that fermented rice-wash water affected selected seedling growth traits, while Widodo et al. (2025) identified effects on stem diameter and flowering in tomato under specific concentration and frequency regimes. The present experiment differs because the water was fresh and unfermented and was not supplemented with a balanced nutrient fertilizer. Fermentation can change nutrient forms and microbial activity, as demonstrated by Nabayi et al. (2021, 2023), so the more limited response here is compatible with a lower and more transient nutrient contribution. Rikhma Sari et al. (2023) also observed growth improvement when rice-wash water was used with an additional nutrient source, reinforcing the importance of formulation context.

Yield response and lack of interaction

Neither treatment factor significantly changed final yield components (Table 3). Under eggshell treatments, fruit number per sample ranged from 21.48 to 24.59, fruit weight per sample from 62.00 to 78.44 g, and fruit weight per plot from 257.22 to 279.33 g. Under rice-wash-water treatments, fruit number ranged from 20.33 to 24.67, sample fruit weight from 66.67 to 72.85 g, and plot fruit weight from 256.89 to 280.56 g. Although A2 produced the highest numerical fruit weight per plot, the difference was not statistically significant. The data therefore do not support a claim that fresh rice-wash water at 250-350 mL plant-1 increased red-chili yield under the conditions of this experiment.

Table 3. Main-effect means for phenology and yield variables

Treatment	Flowering (days)	Harvest (days)	Fruits sample-1	Fruit wt sample-1 (g)	Fruit wt plot-1 (g)
T0: 0 g eggshell	36.67	68.67	24.59	78.44	279.33
T1: 10 g eggshell	35.56	69.33	21.48	69.93	274.22
T2: 20 g eggshell	36.67	68.67	21.93	62.00	257.22
A0: 0 mL rice-wash	37.78 b	69.33 a	20.33	66.67	256.89
A1: 250 mL rice-wash	36.22 ab	69.33 a	24.67	70.85	273.33
A2: 350 mL rice-wash	34.89 a	68.00 b	23.00	72.85	280.56

Note: Different letters within the rice-wash-water factor indicate DMRT differences at 5% for flowering or harvest age. Fruit number and fruit-weight variables were not significant.

The separation between phenological response and yield response is a central finding. Yield is the accumulated outcome of carbon assimilation, nutrient supply, water status, flower retention, fruit set, and fruit filling. A short-lived improvement in early stem growth or a small shift in flowering time will not necessarily increase harvest mass if later nutrient supply remains limiting. Organic and liquid-organic fertilizer studies in chili similarly show that vegetative and yield variables do not always move together. Yuliani et al. (2024) found that certain fertilizer treatments optimized individual vegetative traits without significantly improving several yield components, while Rismayanti et al. (2024) showed that yield responses depend on the nutrient combination rather than simply the presence of an organic input. Pega et al. (2025) obtained stronger red-chili responses when fermented rice-wash water was paired with NPK, suggesting that the rice-wash fraction may be more effective as a complementary rather than standalone nutrient source.

The absence of an eggshell × rice-wash-water interaction further indicates that the two residues did not act synergistically at the tested doses and preparation methods. This may reflect asynchronous nutrient release. Fresh rice-wash water supplies a relatively small pool of dissolved compounds that can be rapidly accessed or lost, whereas eggshell $CaCO_3$ requires dissolution and soil reaction before much of its calcium and liming potential becomes available. Combining them on the same crop does not guarantee that nutrients become available at the same physiological stage. Rombe and Pakasi (2021) showed the feasibility of using both rice-wash and eggshell residues, but their liquid-organic-fertilizer context differs from the present dry-powder plus fresh-water treatment.

Likewise, Nabayi et al. (2023) demonstrated that fermented rice-wash water became more effective when synchronized with a defined mineral-fertilizer supply. The present non-significant interaction therefore provides useful evidence about formulation and timing rather than evidence that the two waste resources are agronomically worthless.

From a circular-nutrient perspective, the results favor a more process-oriented use of household residues. Eggshell should be evaluated after finer grinding, pre-incubation, acidification, composting, or conversion into a liquid or otherwise more reactive calcium source; rice-wash water should be characterized for nutrient content and evaluated under controlled fermentation, repeated application, or partial substitution of a balanced fertilizer. These directions align with current circular-agriculture literature, which emphasizes that waste valorization requires converting residues into forms whose nutrient-release patterns are compatible with crop demand (Gamage et al., 2023; Liu et al., 2024; Sainz-Hernández et al., 2026). They also fit the stage-specific treatment responses observed in comparable horticultural factorial experiments in Algebra, where input effects were expressed only in particular growth or yield variables (Azhari et al., 2025; Hasibuan et al., 2024).

A limitation of the present study is that the chemical composition of the eggshell powder, rice-wash water, and growing medium was not measured. Consequently, the proposed explanation concerning release rate and nutrient sufficiency is mechanistic interpretation rather than direct chemical evidence. The study also evaluated one crop cycle and a relatively narrow range of doses. Future experiments should quantify pH, electrical conductivity, Ca, N, P, and K before and after application; compare fresh versus fermented rice-wash water; include an incubation period for eggshell; and benchmark the residue treatments against a recommended fertilizer treatment. Such measurements would test whether the observed early response represents nutrient supplementation, microbial effects, changes in root-zone chemistry, or a combination of mechanisms.

CONCLUSIONS

Eggshell powder at 10 and 20 g plant-1 did not significantly affect red chili plant height, stem diameter, flowering age, harvest age, fruit number, fruit weight per sample plant, or fruit weight per plot. Fresh rice-wash water produced a more selective response: 250-350 mL plant-1 increased stem diameter at 3 WAP, and 350 mL plant-1 advanced flowering from 37.78 to 34.89 days and harvest from 69.33 to 68.00 days. These early and phenological responses did not translate into a statistically significant increase in fruit number or fruit weight. The interaction between eggshell powder and rice-wash water was non-significant for all variables. The main contribution of the study is therefore the identification of a temporal mismatch between response and productivity: minimally processed household residues can influence early growth or crop timing without improving final yield. For practical use, rice-wash water should be viewed as a supplementary resource rather than a complete fertilizer, while eggshell powder requires processing or pre-incubation to improve short-term availability. Future research should synchronize release rates through eggshell pretreatment, rice-wash-water fermentation, repeated application, and combination with a balanced nutrient source, supported by direct chemical analysis of the inputs and root-zone medium.

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