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RESEARCH ARTICLE

Agronomy

Long-term effects of rice husk biochar on the milling traits of rice (*Oryza sativa* L.) grown in the low country dry zone of Sri Lanka: evidence from a four-season field experiment with urea application

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Abstract: A four-season consecutive field experiment was conducted from the 2023 *Yala* season to the 2024/25 *Maha* season under low country dry zone conditions in Sri Lanka. The objective was to evaluate the combined effect of rice husk biochar (RHB) and urea fertilization on the rice milling traits hardness, chalkiness, bran weight (BW), total milled rice (TMR), hull percentage, degree of milling (DM), brown rice (BR), and head grain (HG) percentages. The rice variety At 362 was used as the test cultivar and the experiment followed a split-plot design with three replicates. The main plot treatments consisted of four RHB levels: 0, 1, 2, and 3 t ha^{-1} (designated as BC0, BC1, BC2 and BC3) with partially burnt paddy husk (PBPH) applied at the Department of Agriculture recommended rate of 625 kg ha^{-1}. Sub-plot treatments included four levels of urea fertiliser: 0, 30, 70, 100 % of the recommended dose (U0, U30, U70, U100, where U100 = 225 kg ha^{-1}). Agricultural-grade urea commonly used by local farmers was applied following standard local practice. Results indicated that a one-time application of RHB combined with seasonal urea significantly enhanced total grain yield peaking at 6.50 t ha^{-1} in season 3 and improved rice milling traits. Higher biochar and urea application rates led to consistent improvements in grain yield and all positive milling attributes, while significantly reducing hull percentage and grain chalkiness across all seasons, demonstrating a residual biochar effect. In comparison, PBPH resulted in significantly lower grain yield and quality improvements compared to RHB treatments. Correlation analysis revealed a strong positive relationship between grain hardness, DM % and TMR %, and a strong negative relationship between hull percentage and BW %. Forecasting models suggest that rice milling traits can be further optimized with RHB application rates exceeding 3 t ha^{-1}. Overall, the integration of RHB with urea provides greater and more sustainable benefits for rice milling traits while increasing productivity under low-country dry zone conditions in Sri Lanka.

Keywords: Rice biochar, grain milling traits, partially burnt paddy husk, urea, rice husk

INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food for over half of the world's population. Ninety percent of rice production and consumption occurs in Asia (Ali et al., 2022). Rice plays a key role in Sri Lankans' daily diets and rural livelihoods. With the increase in the local population, the demand for food increases. Therefore, improving rice productivity and quality has become an urgent requirement in Sri Lanka. Due to the heavy use of synthetic fertilizers and intensive cultivation practices, existing paddy production methods are increasingly unsustainable. Fertilizer leaching and pollution are other issues related to the heavy use of synthetic nitrogen (N) fertilizers (Lai et al., 2023; Gowthami et al., 2022a;

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Adebajo et al., 2022). Industrial urea, the major nitrogen fertiliser used in paddy cultivation, is synthesized from atmospheric nitrogen via ammonia and generally contains negligible concentrations of heavy metals. Therefore, urea itself is not considered a major direct source of heavy metals, especially compared to phosphate fertilizers, which are the primary contributors of cadmium (Cd) and lead (Pb) in agricultural soils. However, in tropical rice-growing systems, heavy metal accumulation may still occur through long-term fertiliser use, irrigation with contaminated water, soil acidification, and the use of other agrochemicals, particularly phosphate fertilizers containing trace Cd and Pb. However, due to the naturally low fertility of many paddy soils, the application of synthetic fertilizers is essential for higher production. Repeated cultivation often worsens this issue, resulting in high acidity and toxic levels of aluminum (Al), iron (Fe), and manganese (Mn) (Butnan & Vityakon, 2023). These challenges highlight the need for sustainable soil management practices to restore soil health, maintain productivity, and protect environmental quality.

One promising solution is biochar, a carbon-rich byproduct produced by pyrolysis, where biomass is burned at high temperatures, usually between 300 and 1000 °C, with limited or no oxygen (Lehmann & Joseph, 2009; Verheijen et al., 2010; Karam et al., 2022). Although biochar research has become popular among scientists in recent years, it has been used since ancient times as a soil amendment. The Terra Preta highly fertile man-made soils found in the Amazon Basin, are a type of biochar used in pre-Columbian civilizations. One of the key characteristics of the carbon contained in biochar is its long-term stability, which helps to improve soil fertility and mitigate climate change (Koyama et al., 2016; Abukari et al., 2018). The high surface area and porous structure of biochar is also useful as a sustainable soil amendment.

Rice husks, the main byproduct of the rice milling process, can be converted into biochar, which reduces agricultural waste by providing an eco-friendly recycling method. Research on the application of rice husk biochar (RHB) has shown significant improvements in various physical, chemical, and biological attributes of paddy soils (Hammer et al., 2015; Rawat et al., 2019). As an example, RHB can improve soil structure, porosity, water retention, and aggregate stability, which are essential attributes for relieving the effects of water stress (Lehmann & Joseph, 2009; Jin et al., 2020) in dry zone rice cultivation. Additionally, applications of RHB can increase pH, cation exchange capacity, and carbon content, which are essential in ameliorating acidic soils. Moreover, RHB can increase soil nutrient retention and availability (Abrishamkesh et al., 2015; Ding et al., 2022; He et al., 2017; Karam et al., 2022). In addition to improving nutrient retention, RHB may reduce heavy metal bioavailability in paddy soils through adsorption within its porous structure (Asadi et al., 2021), surface complexation by oxygen-containing functional groups (Asadi et al., 2021; Chen et al., 2023), ion exchange, mineral precipitation, and pH-induced immobilization (Asadi et al., 2021). The high silicon (Si) content of RHB may further help to reduce heavy metal uptake in rice by strengthening root tissues and reducing the mobility of toxic metals such as Cd (Karam et al., 2022; Tan et al., 2024), Pb (Asadi et al., 2021), and Cr (Karam et al., 2022; Knoblauch et al., 2021). Further, biochar has shown significant enhancement in soil microbial biomass and activity following its application (Steinbeiss et al., 2009; Ali et al., 2021). Because of these positive effects, many field and pot experiments applying RHB have demonstrated improved growth and yield parameters in rice (Asai et al., 2009; Lai et al., 2023; Jeffery et al., 2017).

When considering consumer preferences and market prices, grain milling properties such as hardness, chalkiness, head grain recovery, and milled rice percentage are important parameters. Ali et al. (2022) reported that rice husk biochar (RHB) applications can enhance brown rice recovery, milled rice percentage, and head rice recovery. They also indicated a positive correlation between these parameters and grain composition and starch deposition during grain filling. For example, Ali et al. (2022) observed reductions in chalkiness and higher head rice recovery, while Ali et al. (2020a) and Gong et al. (2020) reported improvements in starch quality parameters such as gel consistency and viscosity with the application of RHB. Other studies on the biochar effect on grain quality concluded that grain quality improved because of better nitrogen availability and enzyme activity in soils treated with biochar (Wang et al., 2014; Ali et al., 2020b). Improved nitrogen availability may also enhance grain protein content (Ali et al., 2020a; 2020b; Li et al., 2023), thereby increasing the nutritional value of rice, which is particularly important for populations relying on rice as a staple food. Although higher grain nitrogen may improve protein content, excessive nitrogen fertilization can compromise food safety and human health indirectly through nitrate contamination of groundwater and enhanced uptake of toxic heavy metals into rice grains (Ali et al., 2020a), soil acidification, and humification (Ali et al., 2020b). Soil acidification increases the solubility and bioavailability of toxic heavy metals (Asadi et al., 2021; Tan et al., 2024). Therefore, improving nitrogen use efficiency while maintaining grain quality remains a critical objective in sustainable rice production.

The effects of biochar on soil properties and crop performance can be seen after several cropping cycles due to its resistance to breakdown by microbes (Lehmann & Joseph, 2009; Bi et al., 2021). Also, the benefits of biochar are not always immediate and can vary based on soil conditions, biochar types, and management practices. Therefore, long-term field studies are needed to understand the cumulative and residual effects of biochar amendments. Although many research findings are available on the application of biochar in tropical countries, there are limited long-term studies over multiple growing seasons especially on the milling properties of rice. Milling properties significantly influence farmers' economic returns and the quality of rice available. The low-country dry zone of Sri Lanka, known for its water shortage and fragile soils, requires more research on sustainable solutions for soil improvement. Therefore, in this study, we conducted four seasonal field experiments to understand the lasting benefits of a single RHB application in season 1 (S1), followed by another three consecutive seasons on rice milling properties under low country dry zone conditions in Sri Lanka.

MATERIALS AND METHODS

The field experiment was conducted at the Rice Research Station in Ambalantota, Sri Lanka to determine the interactive impact of biochar and urea on rice crops cultivated during four consecutive seasons: 2023 *Yala* (S1, from June to September), 2023/24 *Maha* (S2, from November to March), 2024 *Yala* (S3), and 2024/25 *Maha* (S4). The climate is classified as tropical monsoon and the mean maximum and minimum temperatures, mean relative humidity, and mean precipitation values throughout the experimental period are shown in Figure 1.

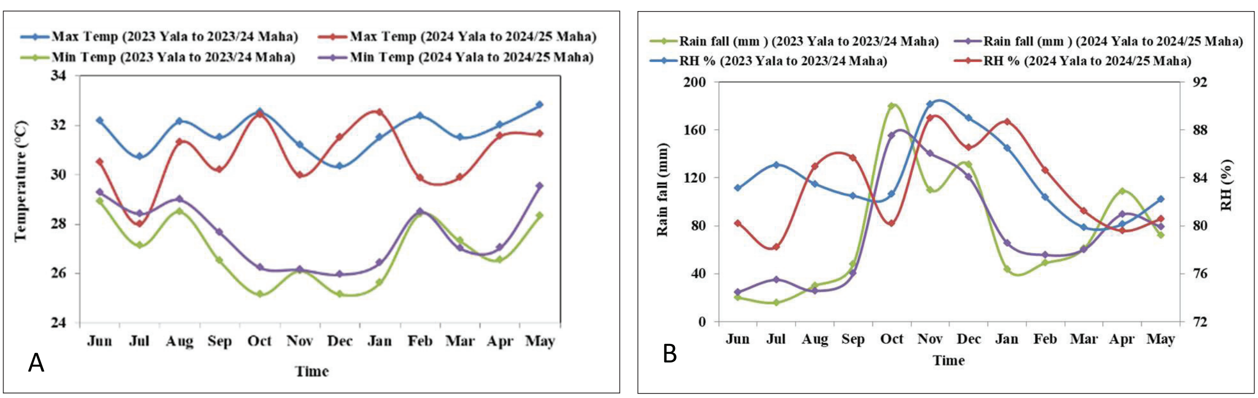

Figure 1: The variation of mean maximum and minimum temperatures (A), relative humidity, and total rainfall (B) during the experimental period from 2023 *Yala* to 2024/25 *Maha* seasons.

The soil is characterized as Grumusol (Mapa et al., 2010) and is of near natural acidity (pH 6.54), electrical conductivity 210 µS cm^{-1}, soil organic matter 1.03%, soil organic carbon 0.74 % with a bulk density of 1.41 g cm^{3}. The rice variety At 362 was used for the experiment. Four different levels of RHB at 0, 1, 2, 3 t ha^{-1} (denoted as BC0, BC1, BC2 and BC3 respectively) and the Department of Agriculture recommended level of partially burnt paddy husk (PBPH) (625 kg ha^{-1}) with four levels of urea at 0, 30, 70, 100 % (U0: without urea fertiliser, U30: 67.5 kg ha^{-1}, U70: 157.5 kg ha^{-1}, U100: 225 kg ha^{-1}) were used as treatments in this experiment. The Department of Agriculture recommended urea fertiliser amount for paddy was considered 100% (DOA, 2013). A commercially available agricultural-grade urea commonly used by local farmers was used in the experiment. Except for urea, all other nutrients were added to each experimental unit according to the recommended rates. The treatment combinations were arranged in a split-plot design with three replicates, with biochar levels as the main-plot factor and urea levels as the subplot factor. The biochar was derived from rice husk. The rice husk was burned in a pyrolyser (thermally insulated chamber) for 8 hours in the absence of oxygen at approximately 500 °C. PBPH was prepared by open environmental burning without temperature control. RHB was added as a one-time application in the first season (S1) and urea was applied in every season. Weather parameters were collected through equipment located in the research field. Milling qualities were determined through standard calculations described by Sultana et al. (2022).

At maturity, the rice plants were harvested from the entire plot and rice grain yields were weighed. The dry weight of the rice grain was determined at 14% moisture content and expressed as kg ha^{-1}. A clean paddy sample of 150 g was de-husked in a milling machine (SATAKE - THU 358, Japan) and the brown rice and hulls were separated. The brown rice (BR) percentage and hull percentage were calculated as described in Equations 1 and 2. The bran was removed from 100 g of BR and polished for 75 seconds in a grain polishing machine (SATAKE TM050C, Japan). The percentage of total milled rice (TMR) was determined from the weight of the polished rice (Equation 3). The polished rice was separated into whole and three-quarter(¾) kernel grains to calculate the percentage of head grains (HG) (Equation 4). The degree of milling (DM) was determined using the amount of TMR and BR using Equation 5. A sample of 100 g of the 75-second milled rice grains was counted and placed in the grain scope (TX - 200) under blue light to calculate chalkiness. Grains showing translucency with a white belly, white back, and white center were counted, and chalkiness was calculated using Equation 6. Harvested grain samples were air-dried for 36 hours until the moisture level reached 13%, after which a grain hardness tester (KIYA 174886, Japan) was used to measure the hardness values. Twenty readings from each parameter were recorded for each replicate.

$$\text{BR (\%)} = \frac{\text{Brown rice weight}}{\text{Paddy weight}} \times 100 \quad ...(01)$$

$$\text{Hull (\%)} = \frac{\text{Weight of hull}}{\text{Weight of paddy}} \times 100 \quad ...(02)$$

$$\text{TMR (\%)} = \frac{\text{TMR weight}}{\text{Paddy weight}} \times 100 \quad ...(03)$$

$$\text{HG (\%)} = \frac{\text{Head grains weight}}{\text{Paddy weight}} \times 100 \quad ...(04)$$

$$\text{DM (\%)} = \frac{\text{Weight of total milled rice}}{\text{Weight of brown rice}} \times 100 \quad ...(05)$$

$$\text{Chalkiness (\%)} = \frac{\text{Number of translucent grains}}{\text{Total number of sample grains}} \times 100 \quad ...(06)$$

Data from the experiments were statistically analyzed, including analysis of variance (ANOVA) and the Least Significant Difference (LSD) test to determine the significance of the effects between biochar treatments. To compare the effects of RHB and PBPH, Dunnett's test (with PBPH as the control) was used. Analysis of variance and graphical presentations were performed using Minitab 21 software for the Windows operating system.

RESULTS AND DISCUSSION

Grain yield was significantly affected by biochar (BC), urea level (U), and season (S), with significant BC × U and BC × U × S interactions (Figure 2). Yield increased across all four seasons with increasing urea level, and this response was further enhanced by higher biochar rates. The highest grain yield was consistently recorded in the BC3U100 treatment, increasing from 5.39 t ha^{-1} in S1 to 6.05 t ha^{-1} in S4, indicating a strong residual effect of the one-time RHB application. In contrast, the lowest yields were observed in the zero-urea treatments across all biochar levels. Notably, in the later seasons, BC3U70 produced yields close to those of BC3U100, suggesting that residual biochar improved nitrogen use efficiency and sustained productivity even at reduced urea rates.

Figure 3 shows the biochar effects on rice grain hardness across four consecutive seasons. Application of biochar had a consistent positive effect on grain hardness. Biochar and season significantly influenced the hardness, but there was no significant effect of urea. Grain hardness increased with the application of higher rates of biochar (3 t ha^{-1}) especially when combined with urea with the highest hardness value of 4.34 N in the BC3U100 treatment in S1. Hardness values showed a gradual reduction with the season. However, the gradual reduction was less with the application of biochar.

The variation of chalkiness during four consecutive seasons with the effect of biochar and urea is shown in Figure 4. Data indicate that the grain chalkiness decreased with increasing biochar levels, particularly under BC2 and BC3 with urea. The significantly highest chalkiness (18 %) was recorded in the BC0U100 treatment in S1, while the significantly lowest chalkiness (8.67 %) was recorded in the BC2U100 treatment in S2, which is not significantly different from the BC3U100 treatment in S2. Only biochar and season, significantly affected the chalkiness; urea alone did not have a significant effect (Figure 4).

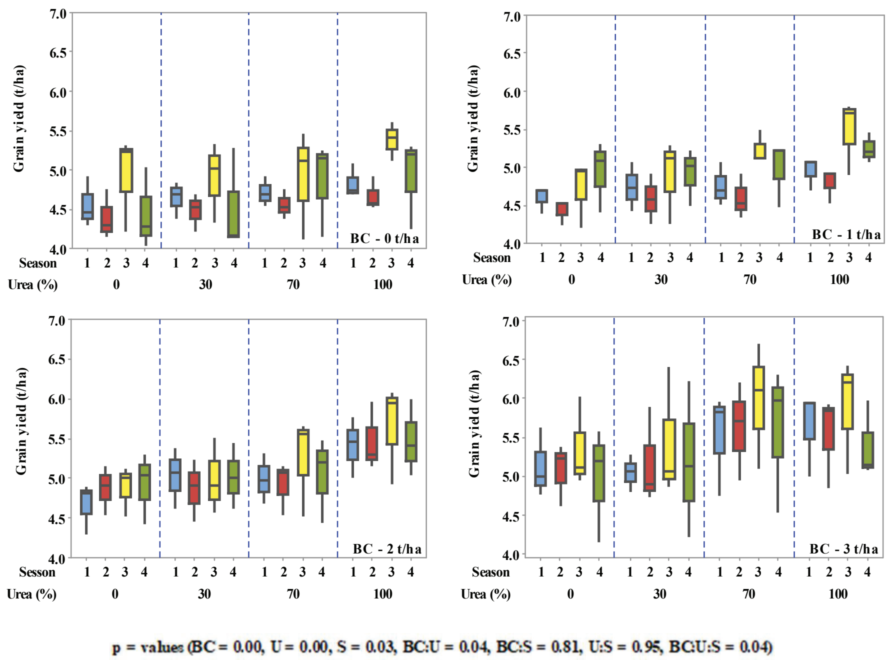

Figure 2: Effect of rice husk biochar and urea levels on grain yield in four consecutive seasons from 2023 Yala to 2024/2025 Maha. The four graphs represent four biochar levels. Numbers from 1 to 4 and 0 to 100 on the x-axis represent the four consecutive cropping seasons and urea levels added, respectively. BC: rice husk biochar; U: urea; S: season.

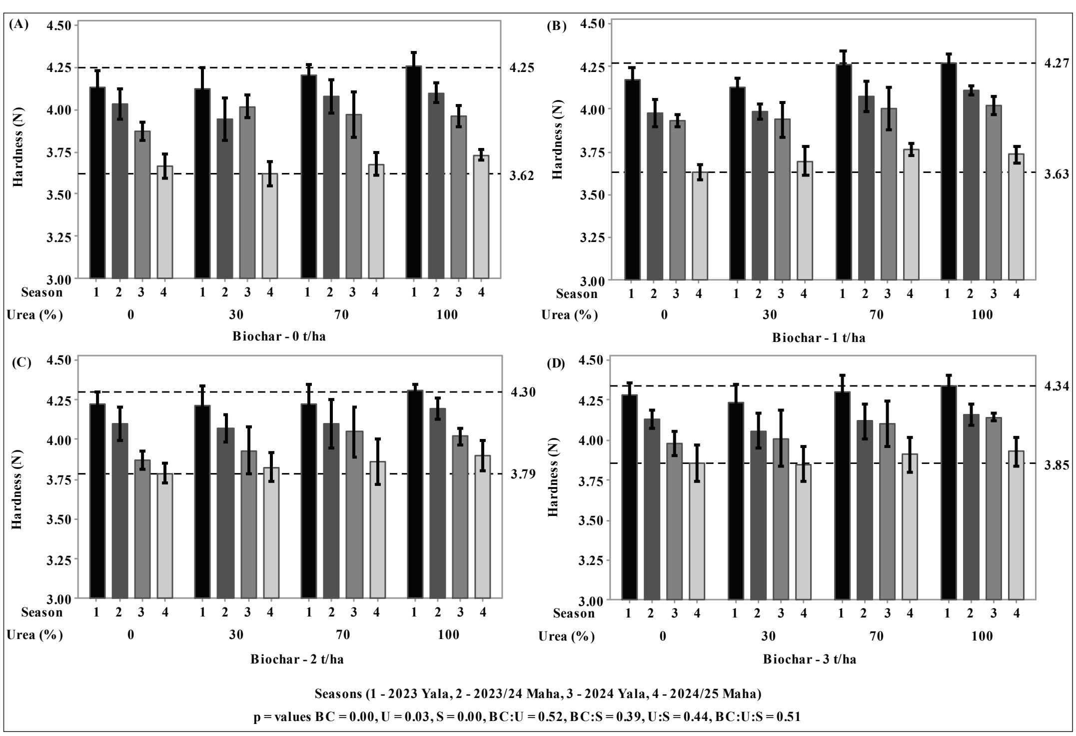

Figure 3: Effect of rice husk biochar and urea levels on grain hardness in four consecutive cropping seasons from 2023 Yala to 2024/25 Maha. The four graphs represent four biochar levels. Vertical bars represent the standard error of the mean. Numbers from 1-4 and 0-100 on the x-axis represent the four consecutive seasons and urea levels added, respectively. BC: rice husk biochar; U: urea; S: season.

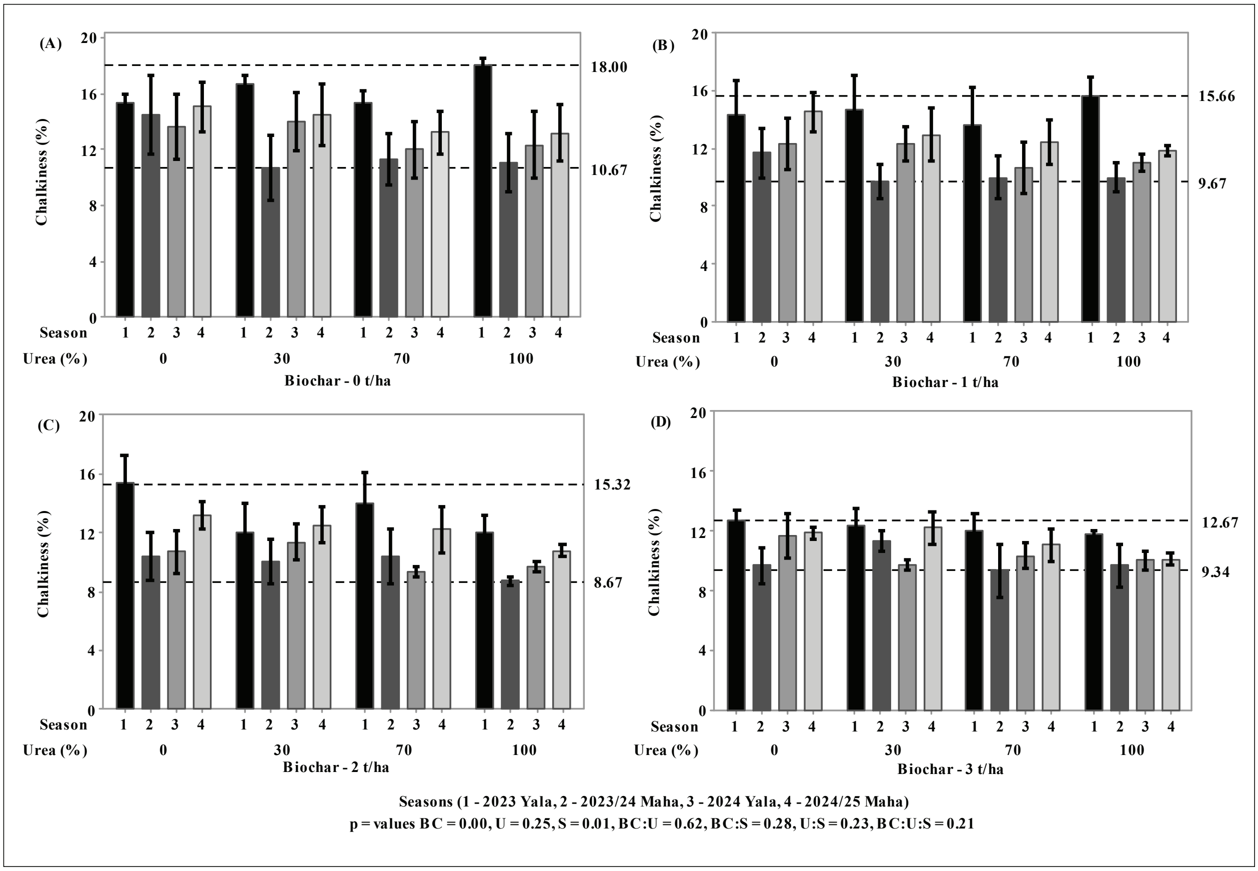

Figure 4: Effect of rice husk biochar and urea levels on grain chalkiness in four consecutive cropping seasons. The four graphs represent four biochar levels. Vertical bars represent the standard error of the mean. Numbers from 1 - 4 and 0 - 100 on the x-axis represent the four consecutive seasons and urea levels added, respectively. BC: rice husk biochar; U: urea; S: season.

Table 1 shows the variation of BR, TMR and HG percentages during four consecutive cropping seasons after the application of different levels of biochar in the first season and different levels of urea in each subsequent season. All three parameters were significantly affected by the rate of biochar, rate of urea, and the seasonal changes. The interaction between biochar and season (BC:S) significantly affected BR %, while the interaction between urea and season (U:S) significantly affected HG %.

The BR% increased gradually with higher biochar rates, reaching the highest levels in BC3U100 (78.53 %, 80.07 %, 80.65 %, and 77.84 % in S1 – S4, respectively). In contrast, the lowest BR % came from the BC0 treatments suggesting that biochar application improves husk removal efficiency, especially when paired with higher urea levels. TMR represents the overall recovery of edible rice after milling and polishing. In all seasons, TMR % increased steadily with more biochar application, with the highest values recorded in BC3U100 (71.20 %, 72.18 %, 73.07 % and 70.49 % in S1 - S4, respectively). HG % represents the proportion of whole grains within milled rice reflecting resistance to breakage during milling. Higher HG % also increases the market price. The highest significant HG % was consistently recorded in the BC3U100 treatment across all seasons.

Table 2 shows the variation of BW, DM, and hull percentages with the application of biochar and urea during four consecutive seasons. Significantly highest BW % and DM % and lowest hull % were observed in the BC3 treatment with higher urea levels in every season. BC:S interaction significantly affected BW %, whereas U:S interaction significantly affected DM %.

Table 1: Brown rice, total milled rice and head grains percentages influenced by different rice husk biochar and urea fertilization levels from 2023 *Yala* to 2024/25 *Maha*

Treat.	BR (%) 2023 *Yala*	BR (%) 2023/24 *Maha*	BR (%) 2024 *Yala*	BR (%) 2024/25 *Maha*	TMR (%) 2023 *Yala*	TMR (%) 2023/24 *Maha*	TMR (%) 2024 *Yala*	TMR (%) 2024/25 *Maha*	HG (%) 2023 *Yala*	HG (%) 2023/24 *Maha*	HG (%) 2024 *Yala*	HG (%) 2024/25 *Maha*
BC0U0	76.63^{d}	78.84^{i}	78.58^{l}	74.64^{e}	67.73^{gh}	69.71^{g}	69.22^{k}	68.08^{g}	59.39^{h}	60.98^{k}	60.91^{i}	59.08^{h}
BC0U30	77.41^{bcd}	78.98^{h}	79.36^{j}	76.39^{bcd}	67.34^{h}	69.99^{f}	70.00^{j}	68.23^{fg}	59.91^{gh}	61.49^{jk}	61.54^{h}	59.93^{h}
BC0U70	77.40^{bcd}	79.61^{d}	79.53^{ghij}	76.21^{bcd}	69.37^{de}	70.69^{d}	70.37^{i}	68.98^{cd}	61.35^{ef}	63.60^{gh}	62.10^{fg}	62.04^{ef}
BC0U100	77.36^{bcd}	79.74^{c}	79.72^{efg}	76.21^{bcd}	69.87^{bcde}	70.85^{d}	70.89^{gh}	68.82^{de}	63.07^{bc}	64.32^{def}	62.31^{f}	62.09^{ef}
BC1U0	76.87^{cd}	79.08^{h}	78.70^{l}	75.85^{d}	67.78^{gh}	70.42^{e}	69.36^{k}	68.37^{efg}	60.57^{fgh}	62.16^{i}	61.91^{g}	60.41^{gh}
BC1U30	77.38^{bcd}	79.26^{g}	79.10^{k}	75.70^{d}	69.91^{bcde}	70.89^{d}	70.33^{i}	69.20^{bcd}	61.22^{ef}	63.14^{h}	62.43^{ef}	61.58^{fg}
BC1U70	77.51^{bc}	79.56^{de}	79.50^{hij}	76.26^{bcd}	69.72^{cde}	71.36^{c}	71.20^{ef}	69.47^{bc}	61.81^{de}	64.06^{efg}	62.79^{de}	62.33^{ef}
BC1U100	77.49^{bc}	79.95^{b}	79.68^{efgh}	77.41^{bc}	70.14^{bcd}	71.37^{c}	71.02^{fg}	69.68^{b}	63.03^{bc}	64.68^{d}	63.38^{c}	63.01^{de}
BC2U0	77.50^{bc}	79.04^{h}	79.43^{ij}	76.08^{cd}	68.37^{fg}	70.68^{d}	70.74^{h}	69.09^{cd}	60.38^{fgh}	61.97^{ij}	62.45^{ef}	65.61^{c}
BC2U30	77.51^{bc}	79.39^{f}	79.80^{def}	75.82^{d}	69.33^{def}	70.64^{de}	71.51^{d}	68.78^{def}	60.89^{efg}	63.14^{h}	63.32^{c}	63.37^{de}
BC2U70	77.52^{bc}	79.55^{de}	79.87^{cde}	77.39^{bc}	70.16^{bcd}	71.47^{c}	71.98^{c}	69.78^{b}	62.64^{bcd}	63.89^{fg}	63.57^{c}	64.38^{cd}
BC2U100	78.50^{bc}	79.96^{b}	80.02^{bc}	77.40^{bc}	69.76^{cde}	71.87^{b}	72.36^{b}	69.81^{b}	63.00^{bc}	64.57^{de}	64.10^{b}	64.15^{d}
BC3U0	77.34^{bcd}	79.21^{g}	79.60^{fghi}	76.28^{bcd}	69.09^{ef}	70.40^{e}	71.12^{f}	68.38^{efg}	61.88^{cde}	69.80^{c}	62.91^{d}	63.91^{d}
BC3U30	77.53^{bc}	79.47^{ef}	79.94^{bcd}	76.39^{bc}	69.52^{cde}	70.82^{d}	71.39^{de}	69.47^{bc}	62.41^{bcd}	71.23^{b}	63.30^{c}	67.67^{b}
BC3U70	77.74^{ab}	79.91^{b}	80.12^{b}	77.05^{ab}	70.78^{ab}	71.76^{b}	72.32^{b}	69.74^{b}	63.06^{bc}	71.54^{b}	64.03^{b}	68.65^{ab}
BC3U100	78.53^{a}	80.07^{a}	80.65^{a}	77.84^{a}	71.20^{a}	72.18^{a}	73.07^{a}	70.49^{a}	64.49^{a}	72.20^{a}	65.10^{a}	69.98^{a}
BC		s*					s*				s*	
U		s**					s**				s*	
S		s*					s*				s*	
BC:U		ns					ns				ns	
U:S		ns					ns				s**	
BC:S		s*					ns				ns	
BC:U:S		ns					ns				ns	

Note: BR: brown rice; TMR: total milled rice; HG: head grains; BC: rice husk biochar; U: urea; S: season; BC0, BC1, BC2 and BC3, represent 0, 1, 2 and 3 t ha^{-1} biochar levels, respectively. U0, U30, U70 and U100 represent 0, 30, 70 and 100% urea levels based on recommended rates, respectively. Values followed by the same letters, within columns are not significantly different at $p \leq 0.05$. * Indicates significant difference at $p \leq 0.05$ and ** indicates $p \leq 0.01$.

Rice bran is a milling byproduct, and the BW % provides an estimate of the proportion of the outer layer (bran) removed during the polishing process. DM % reflects the extent of bran removal during milling; therefore, a higher DM % corresponds to a higher BW %. DM% improved with increasing RHB, and the effect was more pronounced under higher urea content. However, the rate of milling gradually reduced across the seasons indicating the

Table 2: Bran weight, hull and degree of milling percentages as influenced by different rice husk biochar and urea fertilization levels from 2023 *Yala* to 2024/25 *Maha* season.

Treat.	BW (%) 2023 *Yala*	BW (%) 2023/24 *Maha*	BW (%) 2024 *Yala*	BW (%) 2024/25 *Maha*	Hull (%) 2023 *Yala*	Hull (%) 2023/24 *Maha*	Hull (%) 2024 *Yala*	Hull (%) 2024/25 *Maha*	DM (%) 2023 *Yala*	DM (%) 2023/24 *Maha*	DM (%) 2024 *Yala*	DM (%) 2024/25 *Maha*
BC0U0	9.01^{i}	8.27^{k}	9.08^{e}	8.86^{i}	24.96^{a}	27.71^{a}	21.81^{a}	25.35^{a}	75.09^{hi}	74.17^{ef}	74.09^{i}	71.92^{def}
BC0U30	9.15^{h}	8.43^{j}	9.37^{cd}	9.08^{h}	23.15^{cd}	27.25^{bc}	21.39^{b}	23.94^{bc}	75.90^{defg}	74.28^{e}	74.73^{de}	72.02^{cdef}
BC0U70	9.22^{gh}	8.61^{hi}	9.43^{c}	9.17^{g}	23.18^{cd}	27.24^{bc}	21.20^{c}	23.05^{cde}	75.94^{defg}	74.35^{e}	74.16^{hi}	72.09^{cdef}
BC0U100	9.28^{g}	8.54^{i}	9.53^{b}	9.21^{fg}	23.56^{bcd}	27.25^{bc}	20.74^{d}	22.48^{e}	75.97^{def}	74.68^{d}	74.37^{gh}	72.75^{bcd}
BC1U0	9.52^{ef}	8.60^{hi}	9.10^{e}	9.13^{gh}	23.71^{bcd}	26.99^{d}	21.29^{bc}	24.14^{b}	76.18^{cde}	74.35^{e}	74.47^{fg}	71.35^{f}
BC1U30	9.53^{def}	8.65^{gh}	9.39^{cd}	9.26^{ef}	23.8^{bcd}	26.83^{de}	20.89^{d}	24.30^{b}	76.18^{cde}	74.14^{ef}	74.81^{de}	71.81^{ef}
BC1U70	9.60^{bc}	8.71^{fg}	9.41^{c}	9.29^{de}	23.90^{bc}	26.89^{d}	20.49^{ef}	23.73^{bcd}	75.41^{fghi}	74.36^{e}	74.96^{bcd}	72.03^{cdef}
BC1U100	9.60^{bc}	8.78^{ef}	9.42^{c}	9.34^{cd}	23.12^{cd}	27.31^{b}	20.31^{gh}	22.41^{e}	75.91^{defg}	74.69^{d}	74.89^{cde}	72.52^{bc}
BC2U0	9.54^{def}	8.71^{fg}	9.38^{cd}	9.38^{c}	24.09^{b}	27.01^{cd}	20.57^{e}	23.92^{bc}	75.32^{ghi}	74.06^{f}	74.67^{ef}	72.38^{bcde}
BC2U30	9.57^{cdef}	8.81^{e}	9.43^{c}	9.40^{bc}	24.07^{b}	27.33^{b}	20.20^{hi}	24.17^{b}	75.86^{defg}	74.27^{ef}	74.86^{cde}	72.41^{bcde}
BC2U70	9.60^{bc}	8.95^{bc}	9.53^{b}	9.46^{b}	23.58^{bcd}	26.76^{de}	20.12^{ij}	23.02^{cde}	76.41^{bcd}	75.14^{c}	74.96^{bcd}	72.52^{bc}
BC2U100	9.60^{bc}	8.99^{b}	9.54^{b}	9.44^{b}	23.17^{cd}	26.60^{e}	19.97^{jk}	22.30^{e}	76.40^{bcd}	75.29^{bc}	74.96^{bcd}	72.52^{bc}
BC3U0	9.46^{f}	8.85^{de}	9.40^{c}	9.30^{de}	23.18^{cd}	27.26^{bc}	20.39^{fg}	23.68^{bcd}	75.72^{efgh}	74.79^{d}	74.74^{de}	71.87^{ef}
BC3U30	9.54^{def}	8.89^{cd}	9.53^{b}	9.41^{bc}	23.65^{bcd}	27.30^{b}	20.06^{ij}	23.08^{cde}	76.34^{bcde}	75.39^{b}	74.86^{cde}	72.52^{bc}
BC3U70	9.70^{ab}	8.98^{b}	9.59^{ab}	9.46^{b}	23.51^{bcd}	26.58^{e}	19.88^{k}	22.94^{de}	76.73^{abc}	75.47^{ab}	75.12^{ab}	72.98^{ab}
BC3U100	9.74^{a}	9.09^{a}	9.63^{a}	9.63^{a}	23.05^{d}	26.55^{e}	19.35^{l}	22.15^{e}	77.13^{a}	75.54^{a}	75.34^{a}	73.62^{a}
BC		s**					s*				s**	
U		s*					s*				s*	
S		s**					s*				s*	
BC:U		ns					ns				ns	
U:S		ns					ns				s**	
BC:S		s*					ns				ns	
BC:U:S		ns					ns				ns	

Note: BW: Bran weight; DM: Degree of milling; BC: Rice husk biochar; U: Urea; S: Season; BC0, BC1, BC2 and BC3, represent 0, 1, 2 and 3 t/ha biochar levels, respectively, while U0, U30, U70 and U100 represent 0, 30, 70 and 100% urea levels based on the recommended rates, respectively. Values followed by the same letters, within the columns, are not significantly different at $p \leq 0.05$. * Indicates a significant difference at $p \leq 0.05$ and ** indicates $p \leq 0.01$.

reduction of residual effect with the season. Significantly lower DM % was recorded in BC0U0 treatments in every season. Reduced hull % indicates lower generation of agricultural waste during rice milling. Hull % has no significant influence on final consumer preference. The significantly lowest hull% was observed in the BC3U100 treatments.

There was no significant 3-way interaction (BC:U:S) for the grain milling traits measured in this study, indicating that the treatment responses were consistent across seasons. In all seasons, the best milling quality was achieved from the BC3U100 treatment.

The correlation analysis of the heat map among rice grain milling properties is shown in Figure 5. The highest positive correlations were observed between grain hardness and DM % (0.74) and between TMR % and BR % (0.78). The highest negative correlation was observed between BW % and hull % (-0.73). Grain hardness showed a positive correlation with all milling parameters except chalkiness, whereas chalkiness showed positive correlation with all parameters except BW %.

In Sri Lanka, the recommended application rate of PBPH is 625 kg ha^{-1}, primarily to increase the pH of acidic soils. In the present study, the effects of the recommended PBPH rate were compared with different levels of RHB treatments. The comparative results of the RHB and PBPH treatments are presented in Table 3. Among the treatments, BC3 had significantly superior milling quality traits compared with the PBPH treatment, except for BW%, hull percentage, and chalkiness. For TMR%, all biochar treatments showed significantly higher values than the PBPH treatment, whereas grain hardness was significantly greater in BC2 and BC3 than in the PBPH treatment. The zero-biochar treatment showed a significantly lower BW% and higher chalkiness compared with PBPH application.

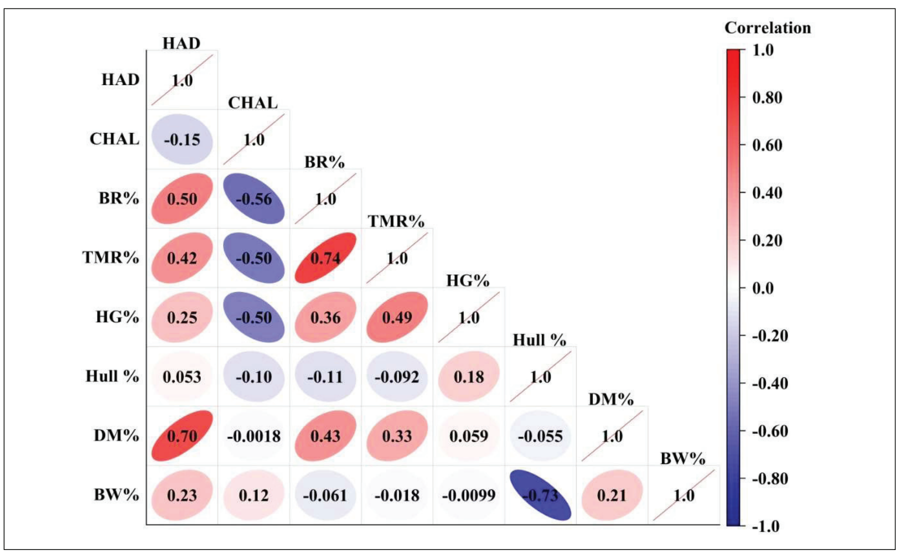

Figure 5: Heatmap correlation matrix representing Pearson correlation coefficients among grain milling traits of rice. CHAL: grain chalkiness; BR: brown rice; TMR: total milled rice; HG: head grain; Hull: rice husk; DM: degree of milling; BW: bran weight; HAD: grain hardness.

Table 3: Dunnet's comparison of milling properties of rice

Treatment	BW(%)	DM(%)	Hull(%)	HG(%)	TMR(%)	BR(%)	CHAL(%)	HAD(N)	GY (t/ha)
PBPH	**9.26**	**74.07**	**24.18**	**63.48**	**68.96**	**77.89**	**11.64**	**3.89**	4.36
BC0	9.03*	74.14	24.05	61.51	69.39	77.44	13.58*	3.90	4.68
BC1	9.21	74.24	23.79	62.43	70.03*	78.13	12.31	3.98	4.75
BC2	9.38	74.60	23.55	62.26	70.45*	78.40	11.25	4.04*	5.10*
BC3	9.40	74.90*	23.39	66.44*	70.74*	78.64*	10.58	4.09*	5.09*

Note: Means labeled with * are significantly different from the control treatment mean at α = 0.05. BW: Bran weight; DM: Degree of milling; Hull: Hull amount; HG: Head grains; BR: Brown rice; CHAL: Chalkiness; HAD (N): Hardness in Newton; GY: Grain yield in t ha-1; BC: Rice husk biochar; PBPH: Partially burnt paddy husk (the control treatment for Dunnett's test analysis).

The forecasting models of the effects of further increases in RHB on grain milling traits are presented in Figure 6. Increasing the biochar level from 3 to 4 t ha^{-1} resulted in increases of 1.61% in grain hardness, 1.43% in HG, and 0.41% in TMR, along with a 6.57% reduction in chalkiness (Figure 6). These findings further highlight the benefits of applying higher levels of RHB as a soil amendment for rice cultivation.

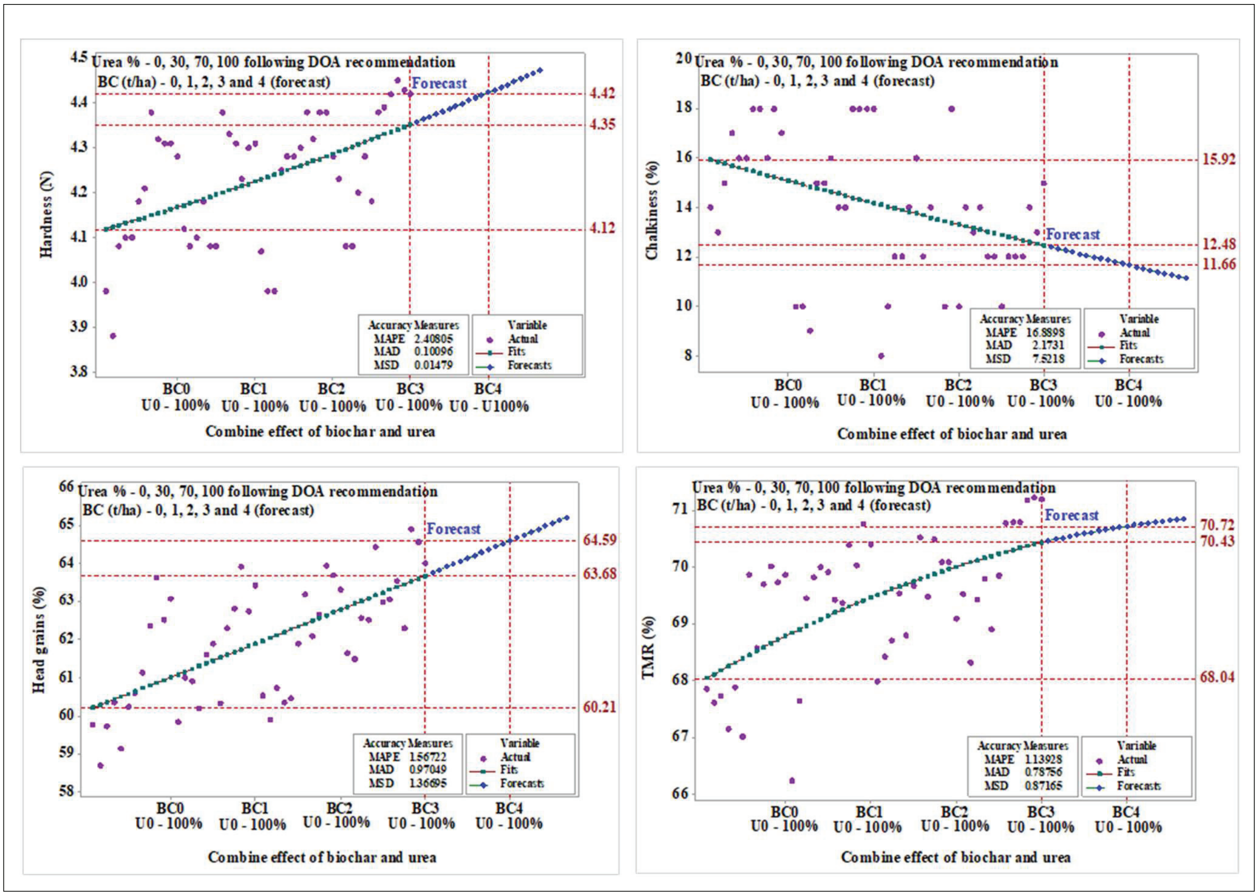

Figure 6: Forecasting the effect of further increments of rice husk biochar on grain hardness, chalkiness, head grain and total milled rice percentages (TMR%).

The data presented in this study indicated consistent positive effects on rice grain yield and milling traits with the application of higher levels of RHB. The residual effect of RHB across seasons shows that even a single application can sustainably enhance grain yield and milling traits over multiple cropping cycles. Similar to this study, many other researchers have reported that the application of biochar, combined with N fertiliser, often exerts positive effects on grain yield and quality traits (Ali et al., 2020a; Chen et al., 2023; Du et al., 2024; He et al., 2024). However, the specific impact of nitrogen on grain quality may depend heavily on the source and rate of application. Earlier studies have reported that synthetic nitrogen fertilization alone can deteriorate rice cooking quality by reducing apparent amylose content and gel consistency (Zhang et al., 2008; Bryant et al., 2012; Iqbal et al., 2022), while excessive nitrogen may also interfere with starch structural order (Zhang et al., 2023). In contrast, under integrated biochar–urea systems, the increased grain nitrogen and protein contents are often associated with improved milling recovery, reduced chalkiness, and better grain appearance (Iqbal et al., 2022; Zhang et al., 2023). Therefore, the positive effects observed in the present study may be linked with balanced nitrogen availability under biochar-amended conditions rather than the effect of urea alone. This improved nutrient balance also may have contributed to enhanced overall productivity (Figure 2), supporting sustained yield trends across multiple seasons. These results agree with previous findings that moderate nitrogen management can sustain grain yield at levels comparable to higher nitrogen rates while simultaneously improving grain texture and starch quality, indicating opportunities for more sustainable fertiliser strategies without yield penalties (Li et al., 2023). While urea contains a small fraction of carbon, most of which is rapidly lost as CO_2 upon application, contributes minimally to soil organic carbon dynamics.

Grain hardness is a critical determinant of rice milling quality and market value. It has significant influences on both HG % and TMR %. Physically harder grains are more resistant to breakage during the intensive hulling and polishing processes, resulting in a higher recovery of whole kernels which give superior selling prices. The results of the present study indicate that a single application of RHB can significantly influence grain hardness. The forecasting models (Figure 6) also suggest that further increments in biochar application beyond 3 t ha^{-1} will continue to enhance grain hardness. The impact of biochar on grain structural integrity is possibly mediated through changes in starch and protein deposition. Gong et al., (2020) reported a direct impact of RHB on grain hardness and reduced chalkiness in several rice cultivars. They noted that grain hardness is closely associated with the structure of starch, especially the proportions of amylose and long-branched amylopectin. Furthermore, Li et al. (2023) reported that nitrogen-induced changes in starch structure may also contribute significantly to this response; higher N availability is associated with smaller, more uneven starch granules, an increase in short-chain amylopectin, and greater relative crystallinity. These structural changes promote a more compact starch organization, which physically harden the grain (Li et al., 2023).

High Si content of RHB also plays a vital role in enhancing grain quality (Karam et al., 2022). Si-rich amendments like RHB have been shown to reduced grain chalkiness, a trait that makes grains more fragile and prone to breakage during milling (Gong et al., 2020; He et al., 2024). The "nutrient sponge" effect of biochar further ensures better grain filling by improving soil nutrient and moisture retention (Karam et al., 2022; Selvarajh et al., 2024).

In this study, the seasonal application of urea may complement this effect by providing the nitrogen necessary for protein synthesis (Gowthami et al., 2022b). Research by Gowthami et al., (2022c) confirms that higher nitrogen levels increase the density of protein bodies, which function as physical binders between starch granules, thereby increasing the mechanical resistance of the grain to milling breakage. However, it is essential to distinguish between the benefits of nitrogen for milling and its potential drawbacks for eating quality. While increased nitrogen contributes positively to raw grain hardness and milling recovery, excessive application can deteriorate cooking quality by reducing apparent amylose content and gel consistency, leading to a harder, less palatable cooked texture (Iqbal et al., 2022; Li et al., 2023). Therefore, the improved hardness and milling efficiency observed in the present study are best attributed to the synergistic effect of biochar-mediated nutrient stabilization and balanced nitrogen supply, rather than the effects of urea alone. Adherence to recommended urea rates in this study ensured optimised grain structural integrity while minimizing potential adverse impacts on soil health or biological activity.

Chalky grains are characterized by a loose and porous arrangement of starch granules in the endosperm, making them highly fragile and prone to breakage due to physical stresses of the milling process (Du et al., 2024). This fragility directly decreases both the HG % and sometimes TMR %. Statistical analysis in this study confirmed this relationship with correlation coefficients between chalkiness and HG % and TMR % recorded at -0.48 and -0.49, respectively (Figure 5). The forecast analysis (Figure 6) suggests that a further increment in biochar applications beyond 3 t ha^{-1} will continue to reduce chalkiness while progressively increasing HG % and TMR %. Consequently, reducing grain chalkiness is a primary strategy for enhancing grain appearance, cooking quality and market value (Ali et al., 2022; He et al., 2024). Therefore, grains with low chalkiness can significantly increase the market price and consumer preference. The results of the present study demonstrate that higher levels of RHB and urea application effectively reduce chalkiness. These findings are consistent with recent reports showing that integrated biochar and nitrogen management can increase grain protein content while simultaneously reducing both the chalky grain rate and the degree of chalkiness (Khan et al., 2023; Du et al., 2024; Jin et al., 2024). In such systems, the higher grain nitrogen content should be interpreted as a marker of improved grain filling and grain quality rather than as a direct cause of quality decline (Ali et al., 2020a).

Beyond soil conditions, the environmental factors such as temperature and rainfall also significantly impact chalkiness formation. Chen et al. (2023) reported that the application of biochar and nitrogen fertiliser can compensate for the environmental effects to some extent. Fahad et al. (2016) also showed that high night-time temperature can increase chalkiness, but the application of RHB and phosphorus fertiliser can reduce chalkiness possibly because of higher water availability. Similarly, Du et al. (2024) and Chakraborty et al. (2021) found that biochar can compensate for the increased chalkiness under no-tillage conditions and drought stress at the grain filling stage respectively. Zhang et al. (2023) also reported a decreasing trend in chalkiness following the application of crop straw biochar in fragrant rice. These inter-seasonal fluctuations are closely linked to the stability of the grain-filling process (Chen et al., 2023). Disruptions during this stage, such as those reported under combined salinity and heavy metal stress, lead to impaired structural integrity and significant reductions in head rice yield (Rifasa et al., 2025). Biochar's role in improving soil structure and nutrient use efficiency promotes more uniform grain filling, thereby preventing the formation of chalky regions (He et al., 2024).

Although heavy metal contamination was not explicitly assessed in the present study, previous research on the At 362 rice variety indicates that stressors such as Cd and As can severely disrupt energy metabolism during grain filling, further increasing grain fragility and chalkiness (Rifasa et al., 2025). Therefore, the use of RHB serves as a robust buffer against both soil and environmental stressors to maintain superior rice quality.

Grain hardness is a fundamental trait influencing milling quality, as demonstrated by its positive correlation with TMR % and DM % (Rifasa et al., 2025). Physically harder grains are more resistant to mechanical breakage during processing, resulting in a higher percentage of whole kernels that command superior market prices (Rifasa et al., 2025). The correlation coefficients of 0.45 and 0.78 in this study quantify the positive relationships of grain hardness of TMR % and DM %, respectively. Enhanced nitrogen availability is likely to contribute to this grain structural integrity by increasing the density of protein bodies, which function as binders between starch granules to harden the physical structure of the raw grain (Gowthami et al., 2022c; Li et al., 2023). The forecasting analysis (Figure 6) suggests that further increases in the application of RHB and urea will continue to improve these parameters. Higher TMR % and DM % scores indicate superior milling efficiency, resulting in a higher yield of polished rice with minimal breakage even if total production remains stable (Rifasa et al., 2025). Conversely, extreme environmental conditions, such as salinity, Cd, and As stress, have been shown to drastically reduce head rice yield and milled grain weight while increasing the degree of milling (Rifasa et al., 2025).

The positive impact of integrated amendments is supported by Alli et al. (2020b) who reported a 5 % increase in TMR % when evaluating the combined effect of cassava straw biochar and nitrogen levels in a two-season study. Similarly, Ali et al. (2022) observed improvements in grain milling attributes following the co-application of biochar and N fertiliser. However, results may vary depending on the variety and management practices; for instance, Gowthami et al. (2022c) reported that while high nitrogen levels significantly increased TMR % in direct-seeded rice, the effect of RHB on the degree of milling was not statistically significant in their specific trial.

Biochar also serves as a critical buffer against environmental stressors that degrade quality. Fahad et al. (2016) observed that while temperature stress can negatively affect milling traits, the application of RHB combined with phosphorus fertiliser can compensate for these effects by improving water availability during grain filling (Ali et al., 2020b). Furthermore, Du et al. (2024) reported an enhanced fine rice rate as a key measure of milling recovery and increased protein content with the application of biochar across both the main season and ratoon seasons. These collective findings underscore that the synergistic effect of biochar and balanced nitrogen fertilization is essential for maintaining the structural maturity and milling efficiency of rice (Li et al., 2023).

Results of this study indicate that treatments receiving higher biochar and urea consistently had significantly lower hull % across all seasons. Although hull % may have less impact on the market price, compared to head rice yield, reducing the hull proportion is a critical indicator of processing efficiency. A significant increase in BR %, the grain remaining after husk removal, was observed with higher rates of RHB and urea treatments suggesting that the integrated application of these amendments promoted endosperm development, thereby lowering the proportion of hull. This improvement in BR % is economically significant, since a higher proportion of harvested paddy can be converted into a marketable product, thus indirectly contributing to the total usable yield (Zhang et al., 2023). These findings highlight that the synergistic effect of biochar and urea is a key driver of long-term productivity, grain filling and endosperm maturation (Ning et al., 2022; Du et al., 2024; Selvarajh et al., 2024).

The observed increase in BR % is corroborated by several recent studies: a meta-analysis by He et al. (2024) found that biochar application significantly elevated the brown rice rate by an average of 0.5 %, with the most favorable effects occurring in soils with low organic matter and high-temperature biochar derived from husks. Du et al. (2024) reported increases of 1.0 % and 1.5 % in BR % under rotary tillage and no-tillage conditions, respectively, following rice straw biochar application. Similarly, Zhang et al. (2023) observed that biochar significantly increased BR % and TMR % for the Meixiangzhan2 (MXZ2) cultivar, although responses can vary by genotype. Chakraborty et al. (2021) found that biochar application significantly increased BR % and HG % even under drought stress indicating that biochar stabilizes grain development during critical growth stages. While Chen et al. (2023) noted that the impact on TMR % can sometimes be inconsistent across seasons, they found that lower biochar dosages generally maintain higher quality of appearance. Furthermore, Gowthami et al. (2022c) noted that while rice husk biochar alone may not always show a statistically significant impact on the degree of milling, the application of urea significantly increased TMR % by enhancing grain boldness.

Results of the present study showed significant improvements in all evaluated milling traits. These findings imply that while urea application alone had a minimal impact, the integrated application of RHB and urea significantly enhances grain filling and minimizes kernel breakage during the milling process. Furthermore, the consistent improvement of milling traits across seasons in treatments with higher biochar and urea levels suggests that a single RHB application has a significant long-term cumulative effect on grain quality in the low country dry zone. These enduring enhancements in grain quality are likely complement the sustained yield increases observed across cropping cycles, highlighting the dual benefits of biochar for agricultural productivity and grain quality.

A comparison with available literature reveals mixed responses regarding the impact of integrated biochar–urea systems on rice milling traits (He et al., 2024). These inconsistencies may arise not only from variations in biochar feedstock, application rates, environmental conditions, and cultivars, but also from differences in fertiliser quality and potential trace-level impurities, which may vary among fertiliser sources. Although urea is generally not considered as significant source of heavy metal contamination, variations in fertiliser composition and soil chemical conditions may indirectly influence enzymatic processes involved in grain development (Li et al., 2023; Rong et al., 2024; Rifasa et al., 2025). Since enzyme activity is highly sensitive to pH, temperature, and ionic strength, such factors may partially explain the discrepancies in grain hardness and other milling traits reported among different studies (Li et al., 2023; Rifasa et al., 2025). While the present study did not assess trace metal concentrations in the applied fertiliser, such effects are likely minimal in urea and remain a speculative but plausible factor for future investigation. Additionally, previous research suggests that varietal differences in resilience to environmental and heavy metal stressors strongly influence milling outcomes, with specific cultivars maintaining greater stability in head rice yield and grain physical traits even under severe stress conditions (Rifasa et al., 2025).

The Department of Agriculture, Sri Lanka through the Yaya programme recommends the application of PBPH at a rate of 625 kg ha^{-1}. Since PBPH is produced from uncontrolled incomplete burning with an ample amount of oxygen, the carbon conversion efficiency is as low as 55% with a high amount of ash (Asadi et al., 2021). Therefore, PBPH paddy husk is technically described as a mixture of ash and high-carbon char (Asadi et al., 2021). Results of the present study indicate that RHB particularly at the 3 t ha^{-1} rate, often outperforms PBPH in enhancing rice milling traits. This superior performance is likely due to the structural stability and high porosity of RHB, which are optimised under controlled pyrolysis conditions (typically 300 – 600 °C without oxygen) to improve soil quality and nutrient retention (Adebajo et al., 2022; Ali et al., 2022b). In contrast, the agricultural benefits of PBPH are less predictable and can vary significantly due to its lack of uniform quality. This inconsistency arises from a higher proportion of unburnt organic matter and volatile compounds, which may negatively affect soil nitrogen transformations and plant growth (Asadi et al., 2021). Furthermore, because of its high ash content and inconsistent chemical nature, PBPH may even cause detrimental effects such as nutrient imbalances or the introduction of phytotoxic compounds, compared to the stable aromatic skeleton of well-produced biochar (Asadi et al., 2021; Butnan and Vityakon 2023; Jin et al., 2024). Ultimately, while stabilized biochar supports consistent improvements in yield and grain quality across multiple seasons, the variable nature of PBPH may constrain its contribution to long-term sustainable productivity.

CONCLUSION

The findings of this study showed significant and sustainable improvements in total grain yield and grain milling traits over four consecutive seasons following the application of RHB in the low country dry zone of Sri Lanka. While urea application alone had a limited impact, its integration with RHB particularly at the rate of 3 t ha^{-1} produced a synergistic effect that significantly enhanced grain yield and milling traits. All measured milling traits showed significant improvements, alongside significant declines in grain chalkiness and hull % in all seasons. These results indicate the residual effect of one-time application of RHB, which maintains grain structural integrity and processing efficiency over multiple cropping cycles. Furthermore, the results confirm that carbon-rich RHB is more beneficial than the PBPH application. In conclusion, the combined application of RHB with the recommended level of urea fertilizer provides a sustainable solution to optimise not only total grain production but also rice milling recovery, quality of appearance, and ultimately the market value of the rice.

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