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Article

Innovative use of Rice Husk Biochar for Rice Cultivation in Salt-affected Soils with Alternated Wetting and Drying Irrigation

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Abstract. Nakhon Ratchasima, Thailand, is the most severely salt-affected area in the country's Northeast region caused by the underlying geology and human activities. In this condition, evaporation of groundwater with salt to the soil surface is an important issue that affects the use of the area primarily for agricultural purposes. This research aimed to improve saline soil quality using rice husk biochar (RHB) to enable rice cultivation. The experiment was designed to limit the evaporation of salty groundwater by cultivating rice in the cement pond. A mixture of different amounts of RHB with four replicates at 0%, 1%, 1.5%, and 2.0% by weight (wt.%) and 500 g dried cow manure were used for rice cultivation. Jasmine rice variety KDML 105 was planted in cement ponds filled with saline sodic soil at pH 10.6, with a total sodium content of 0.83%, electrical conductivity of 68.6 dS/m, and SAR of 11,707. The results indicated that RHB could significantly reduce the soil salinity, EC, Na^+ content, and SAR value while elevating the levels of available macronutrients within just one crop of rice cultivation (120 days). In addition, salt evaporation from groundwater to the soil surface can be limited. The study demonstrated that mixing RHB at 1.5% wt into the saline soil can improve the salted soil and yield the highest rice production. Applying RHB in saline sodic soil for rice cultivated in cement pond is an alternative way for salt-affected areas to reach food security and long-term salted soil revitalization.

Keywords: Biochar, saline soil, soil revitalization, soil amendment, rice cultivation.

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1. Introduction

Soil degradation reduces soils' potential capability, which includes all the processes such as erosion [1], fertility components loss, pollution, desertification, and salinization, etc. [2]. Soil salinity is not a recent phenomenon and has impacted agricultural growth throughout the human settlement, with geological conditions as the underlying cause [3]. Recently, the adverse effects of soil salinity have increased in severity due to improper land use and poor water management. Climate change has also exacerbated the problem through changes in the frequency and intensity of rainfall, drought, increasing temperatures, and evaporation rates. Consequently, in more than 100 countries, salt-affected land areas currently comprise some 10 million square kilometers with continuous expansion [3,4]. Around 23% of cultivated land areas are affected by soil salinity, resulting in a global decrease of agricultural production potential estimated at 124 trillion kilocalories per year [5]. This increasing trend inevitably impacts human food security.

Saline soil degradation crucial affects the ecosystem, land usage, agricultural productivity, and food security [6,7], with negative impacts on sustainable soil management as a significant problem. The degraded soil resulted in the world loss of agricultural supply to approximately 11.9-13.4% over the past five decades [2], while the demand for agricultural products has increased, which is the result of the increase in the world's population. To reverse this trend, the United Nations (UN) has set sustainable development goals (SDGs) as Target 15.3 to combat land degradation and Target 2.4 to ensure sustainable food production systems and increase agricultural productivity by 2030 [8]. Therefore, combating soil degradation by land restoration, soil rehabilitation, and effective land-use planning is significant for sustainable development. Understanding the root of the problems and the suitable applications for the area, including the physical and socio-economic conditions, is critical for success and sustainability [9].

Thailand is an agricultural country and suffers from saline soil problems covering 1.28% (6,611 km^2) of the total land area, resulting in significantly reduced agricultural productivity through osmotic stress and excessive concentration of ions, leading to toxicity and death of plants [10, 11]. Salt-affected areas are often abandoned or sold for salt farming, which further contributes to increased salinity. A total of 52.91% (3,497 km^2) of salt-affected soil is in the northeast region of Thailand. The Maha Sarakham rock formation comprises evaporite deposits overlain by a thin layer of Tertiary alluvium as the cause of saline soil in this area. The soil also has low fertility and insufficient water holding capacity. The northeast region of Thailand is severely affected by saline soil, with Nakhon Ratchasima (14° 58' 16" N, 102° 5' 59" E) the most impacted province [12].

Most previously suggested remedies for solving soil salinity involved physical and chemical methods; however, the biological method is essential for improving the saline soil properties [7, 12-15]. Using biochar to improve saline soil properties is an effective method, reducing labor and costs, and has a long-term positive effect on soil resources [12, 16-18]. Besides, farmers can do this simultaneously as cultivation [19, 20].

Biochar is produced from biomass through pyrolysis, a controlled combustion process conducted under limited oxygen conditions at a controlled temperature [19, 21, 22]. The high carbon (C) content and persistence of biochar offer an opportunity for the long-term storage of C through soil sequestration to mitigate greenhouse gas emissions from agriculture [23, 24].

The porosity, vast internal surface area, and negatively charged ions at the surface make valuable biochar as a soil amendment to improve the soil quality boost crop yields and product quality [20, 25-28], and remedy soil contaminants [29]. Biochar improves the physical properties of the soil, including drainage, aeration, and water retention. Biochar also enhances the chemical properties of the soil through adjustment of pH, conductivity, and cation exchange, thereby improving the ecosystem by increasing soil microbe activities and fertility. Biochar also retains plant nutrients in the soil for more prolonged periods [30-33]. Xiang et al. [34] indicated that the use of biochar resulted in increased root biomass, root volume, and root surface area due to increased root length and the number of root tips of crops. Biochar improves root morphology and vitality [35] and increases root nutrient uptake ability. As a result, plants grown in areas added with biochar show increased growth.

Many studies have shown that biochar effectively improves the physical and chemical properties of many soil types, including clay [36], sandy loam [37, 38], hard and compact [21], acidic [35, 39], and alkaline soils [40, 41], increasing interest in biochar for saline soil improvement and rehabilitation [20, 42]. Wijitkosum [12] found that biochar husk improved abandoned saline-sodic soil properties to allow Jasmine rice cultivation; however, the research indicated significant obstacles as surface evaporation and upward migration of dissolved salts in groundwater through capillary action. This issue presents a significant challenge in rehabilitating salt-affected soils with underlying rock salt material. To deal with this challenge, besides rice husk biochar (RHB) addition to the soil, mitigation of saline groundwater migration was also assessed by growing rice in cement ponds and limiting water supply. The effects of RHB addition on saline soil properties and growth and yield of Jasmine rice (KDML105) were also investigated. A model for solving salinity problems in critical saline areas was created to promote and achieve sustainable agriculture and increase food security in agricultural countries.

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2. Materials and Methods

2.1. Study Area Description

A total of 23.47% of the land area in the northeast region of Thailand (20,494 km^2) is affected by saline soils spread over lowlands (53.33%), plateaus (46.66%), and salt farming areas (0.02%). Saline soil resists cultivation, and abandoned areas account for 3.75% of the total saline soil area [12]. Kham Thale So District in Nakhon Ratchasima Province suffers from critical soil salinity, with 71.47% of the total area comprising saline soil [43] (Fig. 1).

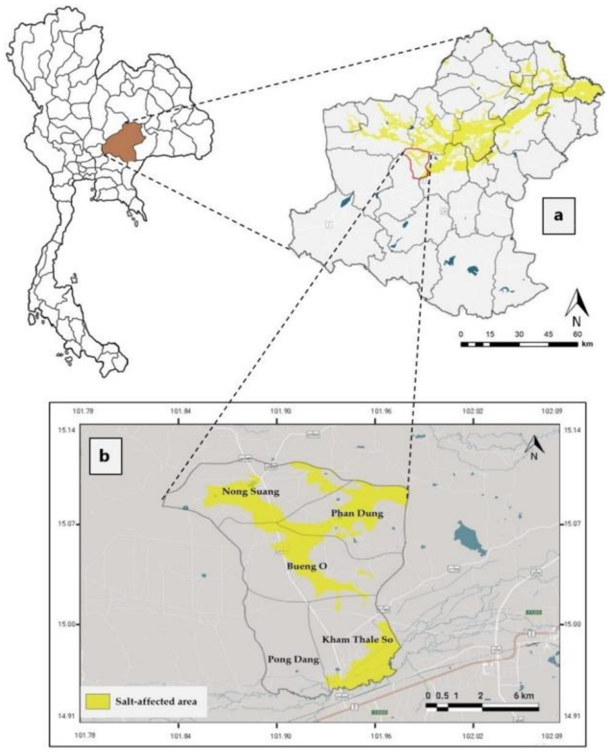


Fig. 1. The salt-affected area in Nakhon Ratchasima Province (a) and Kham Thale So District (b).

The study area is flat, 200–209 meters above sea level, and has an average annual rainfall of 1,000–1,050 mm/year. The maximum annual temperature was recorded at 41°C, with evapotranspiration 552.06 mm/year [44]. The salt-affected area comprises lowland at 29.15% and highland at 69.15%. Water migrates from layers of rock salt beneath the soil to the top surface. The highland showed high salinity distribution potential. Four different concentration levels were found in the salt-affected lowland areas, with 10.75% of the total area as very high level (more than 50%), 5.08% high level (10–50%), 4.75% moderate level (1–10%) and 8.57% low level (less than 1% of salt stains) [45]. Several areas of Kham Thale So District suffer from low agricultural productivity, and some land is no longer cultivable.

2.2. Experimental Design

Jasmine rice (KDML105) was cultivated in-season between August and December 2019. Rice cultivation was conducted in cement ponds to control the ingress of salt from the migration of groundwater. This study followed a completely randomized design (CRD) with four replicates of four treatments, totaling 16 experimental units. The planting materials (saline soil, dried cow manure, and RHB) were mixed at four different levels of RHB. These comprised 0 %wt (RHB-0), similar to regular rice cultivation of local farmers, 1 %wt (RHB-1), 1.5 %wt (RHB-1.5), and 2 %wt (RHB-2). Dried cow manure (500 g) was applied before planting (mixed with soil and RHB) and re-applied (500 g) during the tillering stage.

All the planting materials were thoroughly mixed in cement ponds (80 cm diameter x 40 cm depth with bottom cover) and incubated for 14 d with water level of about 5 cm above the soil surface. The rice was cultivated following the transplantation pattern and wet-dry water management technique [46]. At the tillering stage, the water level was maintained at 5 cm depth in the cement pond and drained at the panicle initiation stage. The water level was increased again at the flowering stage and then drained during the harvesting stage. Rice seedlings at 45 d were transplanted into a cement pond, with 15 seedlings per cement pond (3 seedings per hill) for each treatment.

Rice growth in each cement pond was measured four times at the tillering stage, panicle initiation, flowering stage, and maturation stage. Growth and yield data were evaluated for height, tiller number per hill, panicle number per hill, number of grains per panicle, and grain weight. RHB and organic fertilizer were analysed before planting. The soil was analysed in three parts as before mixing with all planting material, mixed soil in all treatments, and soil after planting.

2.3. Planting Materials and Analysis of Their Properties

The rice husk was dried in the sun for 1-2 days and then processed using the 4 × 200 litters Controlled Temperature Rice Husk Biochar Retort for Slow Pyrolysis Process (patent number: 1601001281).

This furnace applies appropriate, affordable technology and utilizes locally available materials. The furnace was designed to control pyrolysis conditions under limited oxygen availability inside the retort, including air intakes and exhaust holes [12]. The kiln had external and internal furnaces and between those tiers, fuel materials (as heat source of combustion) were placed in the ratio of 60 % (w/w) of rice husk biomass. The retort was designed for controlled-temperature under the slow pyrolysis condition at 450-500°C for approximately 15 hours (until the fuel materials run out).

Analysis of the physical and chemical properties of RHB was carried out following Wijitkosum [12]. The methodology was based on the Standardised Product Definition and Product Testing Guidelines for Biochar used in Soil [47]. The parameters and analysis methods used were as follows. The specific surface area of RHB was analyzed using an automated nitrogen multilayer absorption system, with porosity analysis following the Barrett-Joyner-Halenda (BJH) method. Biochar pH was measured in deionized water and 1M KCl solution at 1:2 (v/v) ratio, while electrical conductivity (EC) was measured at 1:5 (v/v) char: water suspension) after shaking the sample for 1 hour. The biochar cation exchange capacity (CEC) was determined at pH 7 displacement using ammonium acetate extraction. Total nitrogen (total N; Kjeldahl method), potassium (K_2O; atomic absorbance spectrometry (AAS)), total carbon (total C; Shimadzu TOC Tvch), phosphorous (P_2O_5; vanadomolybdophosphoric acid colourimetric method), organic matter (OM; Walkley and Black method) were also measured. Carbon, hydrogen, and nitrogen atom contents (wt%) were measured using a Carbon, Hydrogen Nitrogen, and Sulphur/Oxygen Analyser (Leco CHN628 model). Molar H/C, O/C, and C/N ratios were calculated to predict the biochar stability in the soil [48-51].

Saline soils were collected from Nong Suang, Kham Thale So (Fig. 1). The soil was sampled by a simple random sampling method, with the collection of 1,000 g at a depth of 0–30 cm. The soil was poured onto a plastic sheet, spread, and sun/air-dried for 2–3 d. The dried soil was then sifted through a 2-mm sieve to remove unwanted plants or gravel and homogenized by thorough mixing.

After mixing, the three planting material samples were left for 14 d and then analyzed for their pre-cultivation chemical and physical properties. After 120 d of rice cultivation, the post-cultivation soil was sampled and analyzed. Analysis methods and parameters studied for the soil followed the Land Development Department of Thailand [52]. Chemical soil properties were analyzed for soil pH (pH meter with 1:1 (v/v) soil: water) and CEC (ammonium acetate method). Soil nutrients and elements were analyzed for total N (Kjeldahl method), available P (Bray II method), exchangeable K^+, Ca^{2+} and Mg^{2+} (saturated NH_4OAc extraction and atomic absorption spectrophotometry; AAS) and OM (Walkley and Black method). Analysis of parameters specifying soil salinity contents included electrical conductivity (EC_e), total sodium (total Na), soluble sodium (soluble Na), and sodium absorption ratio (SAR) following the method of the United States Salinity Laboratory Staff [53].

Organic fertilizers used in the study were produced from cow manure of local farmers and analyzed according to the parameters and analytical methods determined by the Land Development Department of Thailand [54]. The parameters and analysis methods were as follows: pH, EC, CEC, total N, K_2O, P_2O_5, Mg, and OM using the same methods as for the biochar analyses.

2.4. Data Analysis

Soil data, rice growth and yield data were displayed as mean ± SD, derived from four replicates. Analysis of Variance (ANOVA) and Duncan's New Multiple Range Test (DMRT) were used to analyze the mean variance and compare significant differences ($p < 0.05$ level) between means using SPSS software.

3. Results and Discussion

3.1. Properties of Planting Materials

Results indicated that RHB had a high specific surface area (41.43 m^2/g) and a total pore volume of 0.03 cm^3/g, with an average pore diameter of 32.73 Å. RHB was slightly alkaline (pH 7.90) with low EC_e (0.35 dS/m). The RHB had a high CEC of 17.34 cmol/kg and a very high OM of 13.06%, directly affecting the improvement of soil properties. The nutritional value results showed that RHB had high total N (0.51%), P (0.29%), K (1.02%), Ca (0.10%) and Mg (0.07%). Elemental composition of RHB consisted of C 45.68%, H 2.22%, N 1.06%, and O 51.04%. The C/N molar ratio was 9.10, O/C 1.12%, and H/C 0.05. RHB had a high content of stable carbon as well as N content. In contrast, H content was slightly lower whether compared RHB of the current study to RHB together (pyrolyzed at 400-500°C) or compared to rice husk biomass [55]. However, compared between rice husk of this study and softwood biochar by similar pyrolysis kilns [27], the C, H, and N contents were lower because biomass type had a significant effect on the properties of the biochar.

The molar O/C ratio showed the polar functional groups and stability of biochar in soil [48, 49]. The O/C ratio of RHB indicated that it could persist in the soil for at least 100 years (O/C > 0.6) [49], while the molar H/C ratio indicated that the carbon structure of biochar was a stable aromatic ring [50]. The European Biochar Certificate (EBC) has established that the biochar stability standard for H/C value should not exceed 0.7 [51]. The EBC standard indicated that RHB contained very stable carbon forms, which can remain in the soil for a long time. The stability of biochar makes it difficult to destroy in the soil environment, especially in tropical regions, and the physical and chemical properties of RHB are beneficial for soil improvement.

The saline soil was characterized as loamy sand with strong alkalinity at pH 10.60 and infertile (OM 0.19%) with a CEC of 2.4 cmol/kg. This result showed that saline soil was deficient in primary macronutrients (total N 203 mg/kg, avail. P 13.9 mg/kg and K 70.2 mg/kg). Moreover, secondary macronutrients found in the soil were also deficient with Ca 540 mg/kg and exch. Mg 1.14 mg/kg Parameters showing soil salt conditions include sodium adsorption ratio (SAR of 11,707), saturated extract electrical conductivity (EC_e) of 68.6 dS/m and total Na of 0.83%. The soil in the study area was saline-sodic soil, according to the USSL [53].

The organic fertilizer was slightly alkaline (pH 8.9) with a high CEC (61.33 cmol/kg) and EC (13.21 dS/m). Organic fertilizer had an OM content of 1.94%, lower than RHB. Plant nutrients in the organic fertilizer were moderate to high, with total N content 1.94%, total P 1.84%, total K 5.22 mg/kg, Ca 2.44 mg/kg and Mg 0.91%.

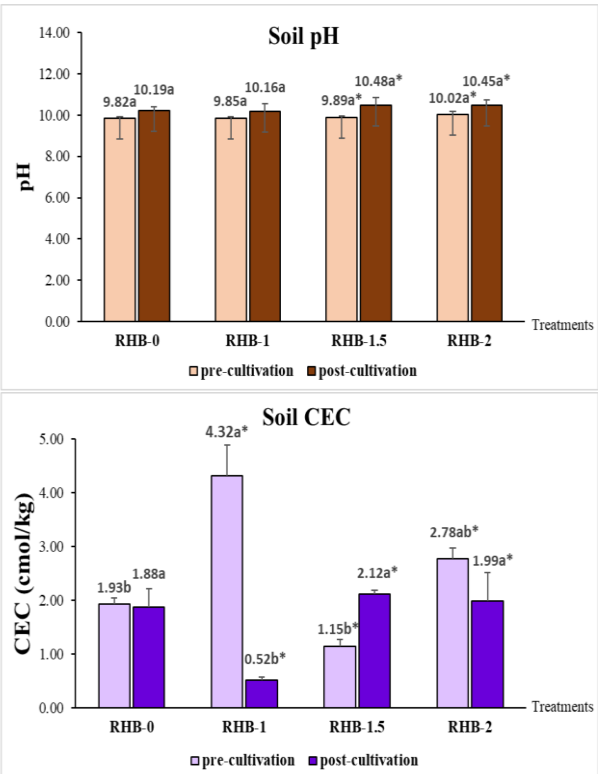
The C/N ratio of 10.6 indicated that the organic fertilizer was fully decomposed.

3.2. Effects of RHB on Chemical Properties of the Soil

After harvesting (120 d), soil samples from all experimental plots were sampled at a depth of 30 cm from the surface to analyze chemical properties.

3.2.1. Soil pH and CEC value

The soil in the study area was strongly alkaline with low CEC and very low OM. Soil mixed with planting material in each pre-cultivation treatment showed changed soil properties, as shown in Fig. 2. Pre-cultivation treatment soil showed pH values of the four treatments ranging 9.82–10.02, increasing slightly (numerically but not significantly) with increasing RHB levels. Soil CEC varied in each treatment, ranging 1.15–4.32 cmol/kg with CEC in RHB-1 significantly higher than RHB-0 and RHB-1.5, while RHB-1.5 recorded the lowest CEC at 3.76 times lower than RHB-1. These results suggest that the dilution effect at high addition rates of biochar can cause soil CEC reduction [56].



Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 2. The soil pH and CEC in different treatments at pre-and post-cultivation.

After cultivation for 120 d (Fig. 2), soil pH increased in every treatment ranging 10.16–10.48. However, no significant differences in pH values were recorded between the four treatments. Changes in pre- and post-cultivation soil pH were significantly different in treatments RHB-1.5 and RHB-2. Soil CEC decreased in all treatments, except for RHB-1.5, while RHB-1 had a significantly lower CEC value than the other treatments. An increase in CEC value of RHB-1.5 due to biochar application at an appropriate rate had a positive effect on the soil. CEC values changed significantly after cultivation for all treatments, except the control (RHB-0), which says that biochar has a significant impact on CEC.

The pH of the soil before mixing planting material was highly alkaline (10.60) when mixed with slightly alkaline planting material such as biochar (pH 7.90) and fertilizer (pH 9.90). As a result, soil in all treatments before cultivation showed increased pH, and soil pH increased after rice planting in all treatments. However, soil pH between treatments is not significantly different due to soil buffer capacity. Changes in soil pH depend on pH of soil amendment and original soil [57]. Previous studies reported that the pH of saline-sodic and sodic soils changed after applying biochar [12, 15, 58-60], resulting from the high amounts of Ca^{2+} and Mg^{2+} in the biochar that were replaced and released H^+ ions in the soil [15].

The high CEC of biochar promotes plants to uptake nutrients such as K^+, Ca^{2+} and Mg^{2+}, and release H^+ from their roots to maintain soil balance [34]. Liu and Zhang [57] reported that carboxylic acids (-COOH) were released from the slow oxidation of biochar, while different soil levels had diverse pH values. Due to water evaporation, topsoil had a higher pH than the lower soil layers, leaving the topsoil ions. By contrast, many studies reported that adding biochar increased soil pH, attributed to Na^+ being washed out of the soil. Soil pH value is an important parameter related to ion precipitation and ion release (e.g., heavy metals and nutrients), controlling soil buffer, CEC values, and soil microbial activity. Changes in soil pH depend on the biochar pH, the amount of biochar, and the pH value of the original soil.

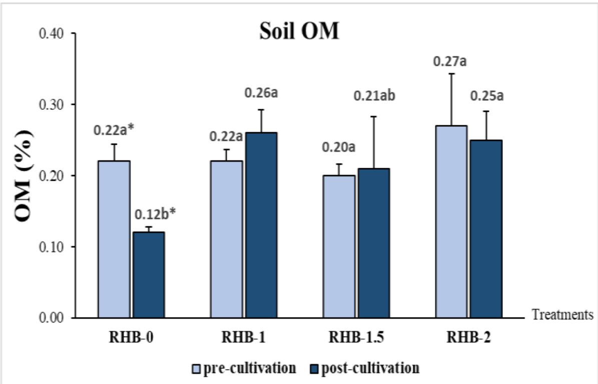
The soil in the study area had CEC of 2.4 mg/kg. After mixing the planting material for 14 days, only soil containing biochar at the rate of 1 %wt and 2 %wt had higher CEC. Changes in soil CEC before and after cultivation were found to be significantly different in treatments using biochar. After cultivation, only the treatment applying 1.5 %wt of biochar (RHB-1.5) increased soil CEC. The CEC in soil was the lowest for the treatment adding 1 %wt of biochar (RHB-1) and significantly different from the other experiments.

Results indicated that adding biochar to soil increased the CEC value if the amount of biochar was appropriate. This was consistent with many previous studies reporting that adding biochar to soil increased CEC in proportion to the amount of added biochar and depended on biochar/soil mixing time due to oxidation of OM by adding COOH groups to the aromatic carbon in the biochar. However, in this study, only the RHB-1.5

treatment showed a slight but not significant increase in CEC value after cultivation, while CEC decreased in the other treatments. Decrease in CEC was caused by the lower content of negative ions, such as sulfate (SO_4^{2-}) or chloride (Cl^-), and due to the ion exchange area decreased in both biochar and organic matter [40, 61].

3.2.2. Soil OM

After mixing the planting materials (Fig. 3), soil had low OM values (0.20–0.27%) but not significantly different in all treatments. The OM value was highest in RHB-2 and lowest in RHB-1.5 and changed after cultivation. The OM increased in RHB-1 and RHB-2 but decreased in RHB-2 and RHB-0. During pre- and post-cultivation, the change in OM indicated that only the control treatment with no biochar added changed significantly.



Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 3. The soil organic matter in different treatments at pre-and post-cultivation.

Adding biochar to soil increased the organic carbon, consistent with many previous research studies. The soil in the study area had OM of 0.19%. After mixing the planting material for 14 days, all treatments showed increased OM in the range of 0.20-0.27%. The increment of OM was not significantly different from the OM in the original soil. Only the biochar-added treatment showed higher OM than in the original soil and the pre-cultivation soil after cultivation. Adding biochar with high OM increased the amount of OM in the soil. Organic matter's degradation and leaching processes occur rapidly in high pH soils, especially in tropical regions like Thailand, along with biochar increase soil porosity and aeration. Thus, added-biochar acts as an intermediate by absorbs and gradually releases nutrients, allowed plant roots to absorb nutrients last longer instead of being abruptly leached away [27, 32, 40].

3.3. Effect of RHB on Soil Nutrients

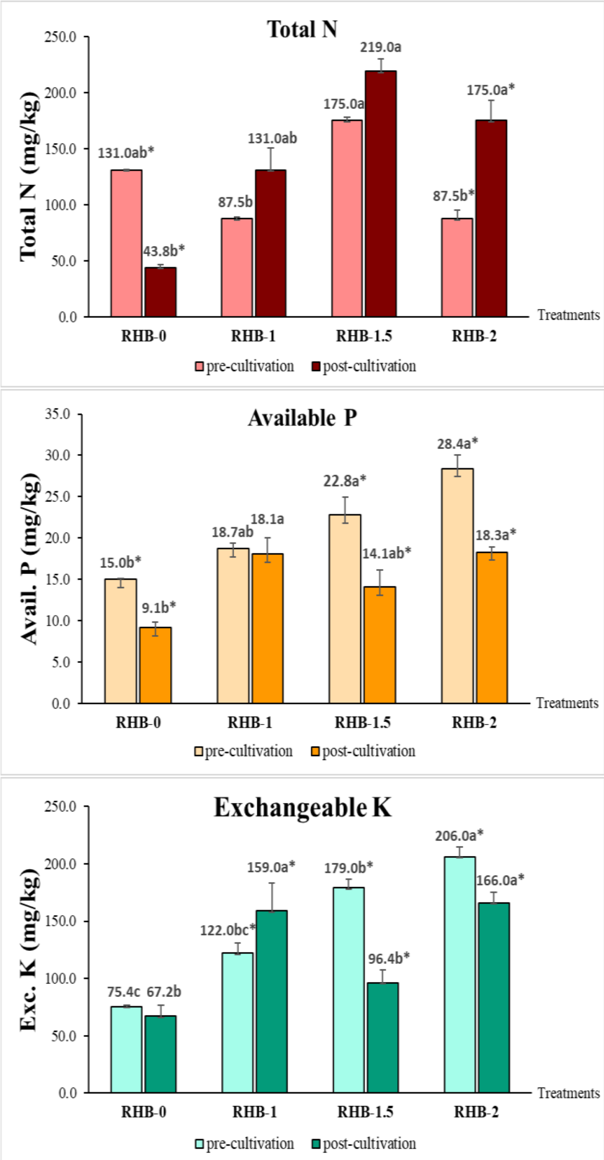
3.3.1. Primary macronutrients in soil

Besides soil salinity, the macronutrient content in soil is also an essential factor influencing plant growth. Soil in the study area is saline-sodic, with high salinity, low fertility and very low macronutrients. Analysis of soil mixed with planting material (Fig. 4) showed that the number of macronutrients in the soil increased with total N in the range 87.5–175.0 mg/kg, avail. P in the range 15.0–28.4 mg/kg and exch. K in the range 75.4-206.0 mg/kg. The total N was highest in RHB-1.5, which was significantly higher than RHB-1 and RHB-2. The avail. P and exch. K were highest in RHB-2 and lowest in RHB-0. The avail. P in RHB-1.5 and RHB-2 differed significantly from RHB-0, while exch. K in RHB-2 was significantly different from the other treatments.

After rice cultivation, the primary macronutrients in soil changed in all treatments (Fig. 4). The total N content increased only in biochar-applied treatments, while controlled treatments had the lowest total N (43.8 mg/kg), with significant differences between RHB-1.5 (219.0 mg/kg) and RHB-2 (175.0 mg/kg). Treatments of RHB-2 and RHB-0 showed a significant change in nitrogen content before and after cultivation. The avail. P decreased in all treatments ranging 9.10-18.3 mg/kg, while avail. P in RHB-0 (9.1 mg/kg) was significantly lower than in RHB-1 (18.1 mg/kg) and RHB-2 (18.3 mg/kg). Decrease in avail. P in the soil before and after cultivation was significant in RHB-2, RHB-1.5 and RHB-0.

The exch. K in pre-cultivation mixed soil treatments increased significantly with increasing RHB addition. However, soil after planting did not show any change in this trend. Results indicated that exch. K increased only in RHB-1 (159.0 mg/kg), while exch. K in the other treatments decreased. Reduced exch. K content was presumed to occur because of increased biochar uptake by the plant. Salt-tolerant rice (KDML105) balances the Na/K ratio, thus increasing the absorption of K [62, 63]. RHB-0 had the lowest exch. K at 67.2 mg/kg, similar to exch. K in the soil before planting. Changes in soil between pre- and post-cultivation showed that exch. K altered significantly in treatments that applied biochar.

Results indicated that the optimal rate of biochar (1.5 %wt) increased nitrogen in the soil after cultivation. The RHB-1.5 treatment was the only experiment that increased soil nitrogen content after cultivation.



Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 4. Total N, available P, and exchangeable K in the soil at pre-and post-cultivation.

The addition of biochar resulted in an increase in soil nitrogen compared to the pre-cultivation of mixed soil. This finding concurred with Ye et al. [22], Haider et al. [64], and Bai et al. [65], who found that applying biochar in crop cultivation increased soil nitrogen content. The N content in biochar strongly affects soil microbial activity and the soil nitrogen cycle, both for nitrification and denitrification. Applying biochar to the soil increased the efficiency of N adsorption and N utilization of plant roots and improved plant growth [35].

The amount of avail. P in the soil after cultivation in treatments with RHB at all rates (1 %wt, 1.5 %wt, 2 %wt) was higher than in the original soil (avail. P of 13.9 mg/kg). Similarly, the application of biochar significantly increased the amount of exch. K in the soil. The amount of avail. P and exch. K increased with the amount of biochar applied. Soil after cultivation in the fertilized treatment (RHB-0) showed avail. P and exch. K lower than the original soil (exch. K of 70.2 mg/kg).

Gunarathne et al. [66] indicated that nitrification resulted in less N and more K uptake by plants due to competition between these two ions. Simultaneously, Saifullah et al. [17] proposed that low pH biochar was effective in soil N retention and reduced ammonia evaporation in saline-sodic and sodic soils.

The soil pH is a critical factor in P precipitation as phosphate. Both P adsorption and precipitation occur when biochar and phosphorus fertilizer are added to a saline-sodic soil. A pH range of 5.5–7 was optimal for P release, while a pH above 7 decreased available P. High calcium content in the soil at pH 8.00 led to calcium and phosphate quickly binding and precipitating, resulting in decreasing available P level [7, 41, 67]. Therefore, biochar can directly affect the soil pH, as well as the available P. Biochar with a high amount of Ca^{2+}, Mg^{2+}, Al^{3+} and Fe^{3+} can also absorb P [26, 68].

3.3.2. Secondary macronutrients in soil

Pre-cultivation mixed soil (Fig. 5) had exch. Ca of 417-509 mg/kg, with the lowest value in RHB-2 and highest value in the RHB-1. The exch. Mg ranged 0.53–1.28 mg/kg, with RHB-2 at 1.28 mg/kg and significantly higher than RHB-1 (0.58 mg/kg) and RHB-1.5 (0.53 mg/kg).

After cultivation for 120 d (Fig. 5), secondary macronutrients increased in all treatments. RHB-1 had the highest exch. Ca of 837 mg/kg and significantly different from the other treatments. The exch. Mg had values ranging 1.18-1.78 mg/kg, with highest in RHB-1 and lowest in RHB-0 but with no significant differences. Secondary micronutrient contents in the soil before and after planting showed that exch. Ca significantly changed in all treatments applying biochar. By contrast, exch. Mg level between pre- and post-cultivation showed no significant differences. Levels of exch. Ca and exch. Mg in the soil after cultivation were higher than in the original soil, especially in treatments with biochar at 1 %wt and 1.5 %wt.

Adding biochar to the soil directly increased exch. Ca^{2+} and exch. Mg^{2+}, as biochar, had high CEC and high surface area with a large number of cation exchange reactions. Moreover, exchange on biochar surface area between Na^{+} and Ca^{2+} or Mg^{2+}, resulted in increased exchangeable Ca^{2+} and Mg^{2+} concentrations, while Na^{+} content decreased [14].

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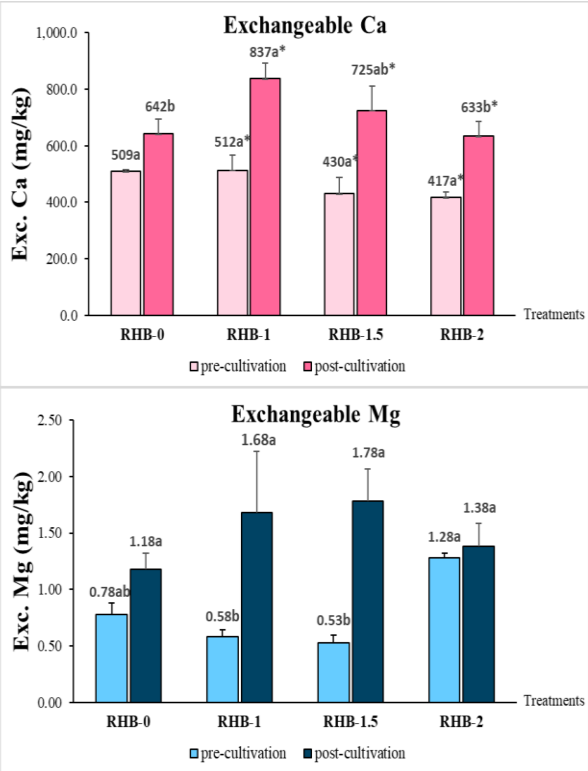


Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 5. Exchangeable Ca^{2+} and Mg^{2+} in the soil at pre-and post-cultivation.

3.4. Effect of Rice Husk Biochar to Remedy Saline Soil

3.4.1. Soil EC_e, soluble Na and total Na

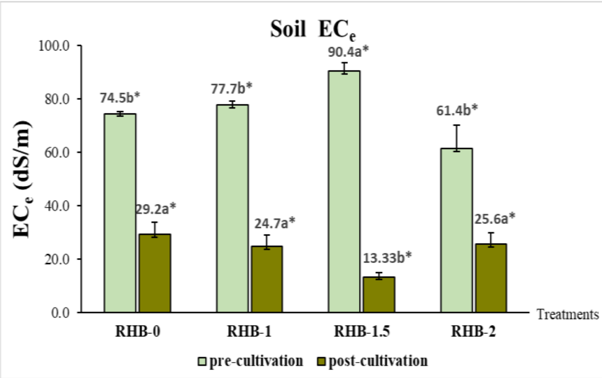
The electrical conductivity analysis in soil mixed with planting material showed that the RHB-1.5 treatment had significantly highest EC_e than the other three treatments with EC_e values ranging 61.4-77.7 dS/m but with no significant difference (Fig. 6). After rice cultivation, soil EC_e decreased in all treatments, with the lowest value in RHB-1.5 (13.33 dS/m) and the highest in RHB-0 (29.2 dS/m). Only the RHB-1.5 treatment showed a significant difference in EC_e from the other treatments. Changes in soil EC_e before and after planting were significantly different in all treatments. Soil EC_e decreased in every treatment compared with the original soil in the area (68.6 dS/m). After applying biochar, soil EC_e values were significantly lower than those with cow manure fertilizer.

Change in total Na soil content after cultivation was in accordance with the EC_e content. In every treatment before rice cultivation (0.74-0.91%), Total Na decreased significantly after rice cultivation in all experiments (0.18-0.36%), as shown in Fig 7. The RHB-1.5 treatment had the lowest total Na content (0.18%). Biochar and fertilizer applications reduced the total Na content in the original soil. However, in the other treatments with two biochar rates (RHB-1; 0.30%, RHB-2; 0.36%), total Na was not significantly different from total Na in the fertilized treatment (RHB-0; 0.28%). Therefore, another soil salinity content parameter was analyzed, namely soluble Na content in the soil.

Results showed that soil soluble Na contents in all treatments after rice cultivation (65-358.1 mmol/l) were significantly lower than before cultivation in all experiments (630.2-1,327.4 mmol/l) and the same direction as total Na values (Fig. 7). Treatments with biochar at all rates significantly reduced soil soluble Na content compared to organic fertilizers. RHB-1.5 had the lowest soluble Na soil content at 65 mmol/l and 5.51 times lower than the treatment with organic fertilizers (358.1 mmol/l). Therefore, using biochar improved the properties of saline-sodic soil. When applying biochar to the soil at 1.5 %wt, the salinity level decreased from extremely high (EC_e 68.6 dS/m and total Na 0.83%) to high (EC_e 13.33 dS/m and total Na 0.18%).

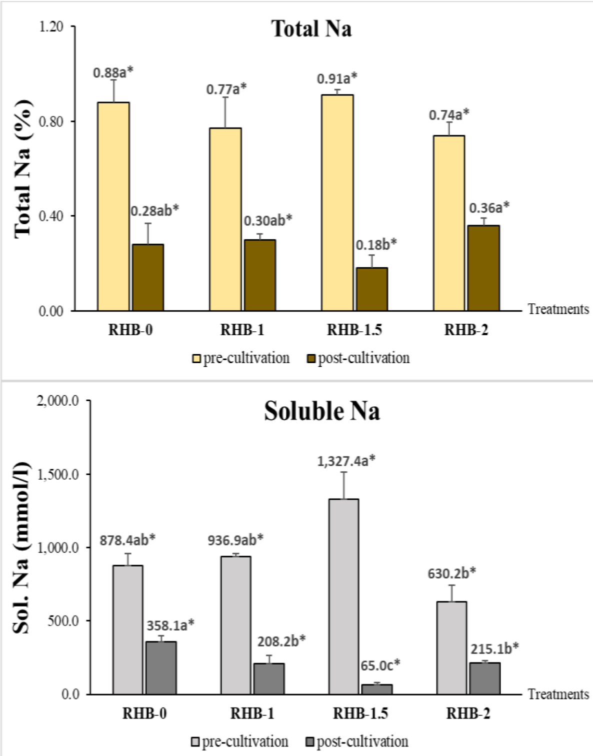
Soluble Na level in each treatment for pre-cultivation soil mixtures ranged 630.2–1,327.4 mmol/l. Values significantly decreased in post-cultivation soil mixtures ranging 65–358.1 mmol/l. Moreover, between the four treatments, soluble Na of RHB-1.5 was significantly lower than the other treatments. The pre-cultivation total Na content of soil mixtures in each treatment ranged 0.74–0.91% but decreased significantly to 0.18–0.36% in post-cultivation soils. Similar to soluble Na, RHB-1.5 gave significantly lower values than the other treatments.

Previous research reported that biochar could bind Na^+ in soil solutions and increase K uptake efficiency of plants, resulting in decreased soluble Na and total Na contents over time. Akhtar et al. [13] considered the Na^+ adsorption mechanism of biochar to be temporary since Na^+ is not as strongly adsorbed to negatively charged surfaces of biochar than other divalent cations, causing lower Na uptake by plants or reduced by-pass flow. Another possible mechanism involves the high content of biochar exchangeable Ca^{2+} and Mg^{2+}. The exchange between these cations and Na^+ in the soil leads to a reduction in Na^+, while sodium content in soil decreases as added biochar increases.



Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 6. The soil electrical conductivity in different treatments at pre-and post-cultivation.



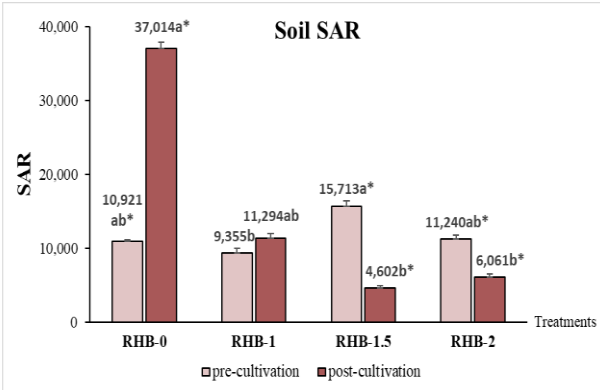
Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 7. Soluble Na and Total Na in the soil at pre-and post-cultivation.

3.4.2. Soil SAR

The SAR of the pre-cultivation soil mixture in each treatment ranged 9,355–15,713, while in the post-cultivation soil mixture, it ranged 4,602–37,014. The SAR of post-cultivation RHB-0 and RHB-1 soils increased compared to pre-cultivation (RHB-0 was significantly increased) but the SAR of post-cultivation RHB-2 and RHB-3 soils significantly decreased. Thus, the SAR of RHB-0 in post-cultivation soil was significantly higher than in RHB-1.5 and RHB-2 (Fig. 8).

The SAR refers to the exchangeable Na in the soil solution. This is the ratio between Na^+, Ca^{2+} and Mg^{2+}, in which the concentration of ions depends on the type and amount of added biochar [15, 69, 70]. In other words, decreasing the amount of Na^+ or increasing the amount of Ca^{2+} results in a decreased SAR value. However, SAR values can be reduced by adding organic or chemical fertilizers to replace Na^+ with other ions. Similar results are showing SAR values of saline soils decreasing significantly after rice cultivation were previously reported [12, 16, 51].



Note: Data are shown as the mean of four replicates. Different letters indicate significant differences between the four treatments ($p < 0.05$). The * indicates significant differences between the mean of pre- and post-cultivation data ($p < 0.05$).

Fig. 6. The soil SAR in different treatments at pre-and post-cultivation.

3.5. Effect of RHB as a Soil Amendment on Rice Growth in Cement Ponds

With a controlled amount of water, the first crop of rice cultivation in cement ponds did not significantly differ in rice height at each developmental stage or between treatments (Table 1).

The average number of grains per spike (Table 2) of RHB-1.5 was highest (17.20) followed by RHB-0 (14.90), RHB-2 (7.80), and RHB-1 (4.30). A similar trend was seen for grain weight (Table 2), where RHB-1.5 had the highest average seed weight (18.67 g) followed by RHB-0 (15.55 g), RHB-2 (5.63 g), and RHB-1 (0.93 g). Grain weight in RHB-1 was significantly lower than in the other treatments. Thus, rice growth and yield were highest in RHB-1.5 followed by RHB-0, RHB-2, and RHB-1, respectively.

Table 1. Height of rice in each treatment at different growth stages.

Treatments	Height (cm) of rice plant according to growth period			
	Tillering	Panicle initiation	Flowering	Harvesting
RHB-0	34.25 ± 7.448	37.00 ± 13.734	38.85 ± 21.820	38.55 ± 23.130
RHB-1	32.05 ± 5.777	31.70 ± 9.078	32.50 ± 12.588	32.05 ± 12.550
RHB-1.5	39.10 ± 16.176	40.10 ± 21.419	41.00 ± 25.096	39.25 ± 25.710
RHB-2	36.35 ± 12.973	36.15 ± 17.501	36.45 ± 18.379	36.30 ± 18.070

Data are shown as the mean ± SD, derived from twenty independent repeats. No significant differences between means was observed.

Table 2. Number of rice grains per spike and yield (weight) of rice grains in each treatment.

Treatments	Number of grains/spikes	Grain weight (g)
RHB-0	14.90[a]	15.55[a]
RHB-1	4.30[a]	0.93[b]
RHB-1.5	17.20[a]	18.67[a]
RHB-2	7.80[a]	5.63[a]

Data are shown as mean value derived from four independent repeats. Means with a different letter are significantly different.

Salt-tolerant rice (KDML105) can grow in low to moderate saline soils and has an adaptive mechanism for salt toxicity. Therefore, biochar application did not result in significant differences in rice growth compared to RHB-0 in the first crop. The mechanism of plant adaptation to salt toxicity is to balance the Na/K ratio. In saline soil conditions, plant absorbs and accumulates Na within the tissues, while the amount of K is decreased, thus, rice needs to be balanced ratio by increasing K uptake [62, 63]. As observed in results in the decreased exch. K of all treatments after cultivation, except for RHB-1, which is consistent with the rice growth of RHB-1 was lowest.

Wijitkosum [12] also found that the effect of biochar was not related to the amount added in a dose-dependent manner. However, growing rice in cement ponds with a wet-dry water management method decreased the amount of water required compared to cultivation in paddy fields, which is beneficial for agricultural areas with low water resources such as Nakhon Ratchasima. Nevertheless, the difference in rice growth between cement ponds and paddy fields was not clear. Rice grown in paddy fields had the highest growth in RHB at 2.0 kg/m², followed by 4.0 kg/m² and 3.0 kg/m² [12], whereas in this study, rice growth was best in RHB at 1.5 %wt followed by 0, 2 and 1 %wt respectively. In both studies, differences in rice growth were not significant. Moreover, the cultivation of only one rice crop (120 d) might not give precise results. Changing soil properties to be more suitable for rice growth requires more time. Nevertheless, consistent results from this research and previous research by Wijitkosum [12] suggest that biochar can decrease salt-affected soil salinity within 120 d.

Biochar plays an important intermediate role in various reactions of soil solutions. For instance, biochar gradually absorbs and releases sodium, thereby reducing toxicity in plants which generally absorb high levels of sodium. Furthermore, because biochar is highly stable, it remains in the soil for a long period of time [48, 49, 51]. Several studies have indicated that biochar can continuously improve soil properties and increase crop yields for more than one-crop cycle period with the addition of single-time biochar [71-73]. Furthermore, a single-time biochar application with dried cow manure results in higher rice yields than soil cultivated and applied with cow manure only [12].

The salt-affected soil of the study area is either uncultivable land or has low agricultural productivity, causing farmers to suffer a continuous loss of income. Thus, farmers abandon these bare and fallow areas without crops covering the soil surface. In addition, some farmers might convert their land into salt farming, resulting in exceedingly widespread salt-affected soil.

However, compared to untreated saline soil in the study area, biochar application improves saline soil properties enabling cultivation and increased agricultural productivity. As a consequence, it positively affects the quality of life of farmers in the long term, the impact on sustainable ecosystems, and food security. Moreover, raising awareness and offering guidance to local people regarding rice cultivation in saline soil within cement ponds by adding biochar is an alternative solution for salt-affected soil problems by considering region-specific conditions. Additionally, biochar is a useful tool for sustainable management in combating land degradation and sustaining food production.

4. Conclusions

The dissolution of rock salts beneath the groundwater's study area results in saline groundwater evaporating to the soil surface, especially during the dry season. Therefore, rice cultivation in bottom-covering cement rings reduces the impact of saline groundwater. In addition, rice cultivation by alternate wetting and drying irrigation decreases the water required, in comparison to paddy field cultivation. This is particularly necessary for cultivating areas with insufficient water resources, such as Nakhon Ratchasima.

The effect of RHB as a soil amendment was studied at addition levels of 0, 1, 1.5, and 2 %wt to saline soil. Results demonstrated that RHB at 1.5 %wt gave the highest rice yield and was suitable for growing Jasmine 105 rice in saline soil in a cement pond. RHB at 1.5 %wt was the only treatment that increased the CEC value while decreasing salinity parameters. The addition of RHB is one of the alternatives for reduced salinity and improved soil properties as more suitable for cultivation. However, when applying biochar as a soil amendment, the type and amount of added biochar, type and characteristics of the soil, and type of plant all need to be considered. Biochar has specific properties, and its mechanisms in combating soil salinity require further elucidation.

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