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Abstract

Rice serves as the cornerstone of Cambodia's agricultural economy and food security; however, its cultivation faces persistent challenges related to soil fertility, nutrient management, and fertilizer leaching. This dissertation investigates the potential of rice husk-derived biochar as a sustainable soil amendment aimed at mitigating nutrient loss, enhancing rice yield, and improving grain quality. With Cambodia's abundant supply of rice husks and their high silica content, biochar emerges as a locally viable solution for boosting soil health. The study, conducted over two years at the Cambodian Agricultural Research and Development Institute, comprised greenhouse column experiments that explored the interactions between biochar and chemical fertilizers across various soil textures and irrigation methods.

First-year experiment: The focus was on a single soil type to evaluate the combined effects of rice husk biochar and chemical fertilizers on nutrient leaching and rice performance. Results showed that the application of biochar at 4 t ha^{-1} together with chemical fertilizers (CHEM + BIO4) significantly reduced ammonium (NH_4^+) and nitrate (NO_3^-) leaching compared to fertilizers alone, particularly from the plow sole. This reduction was attributed to the sorption capacity of biochar. Furthermore, CHEM + BIO4 improved rice yield, biomass, tiller number, panicle length, grains per panicle, and grain weight per panicle. However, biochar did not significantly reduce phosphate (PO_4^{3-}) losses, suggesting its effectiveness is greater for nitrogen management.

Second-year experiment: The scope expanded to include clay (S1) and sandy loam (S2) soils under two irrigation regimes, continuous flooding (CF) and alternate wetting and drying (AWD). Treatments included chemical fertilizers alone (T1) and in combination with biochar at 4 t ha^{-1} (T2) and 6 t ha^{-1} (T3). Across both soil types and irrigation methods, the T3 treatment (CHEM + BIO6) achieved the highest dry grain yields and protein content while significantly lowering losses of NO_3^-, NH_4^+, and PO_4^{3-}. Although amylose content did not differ among treatments, biochar application increased plant biomass and chlorophyll content, underscoring its positive effect on crop performance.

Overall, the two-year findings highlight that rice husk biochar, particularly at rates of 4-6 t ha^{-1}, can enhance nutrient retention, increase rice yield and protein content, and support more sustainable water and nutrient management in Cambodian rice systems. This research contributes to the growing body of evidence on biochar’s role in climate-smart agriculture. Moreover, while both studies demonstrate clear short-term advantages, long-term field trials remain critical to evaluate sustained impacts on soil health, yield stability, and economic viability.

Résumé

Le riz constitue la pierre angulaire de l'économie agricole et de la sécurité alimentaire du Cambodge ; cependant, sa culture se heurte à des défis persistants liés à la fertilité des sols, à la gestion des nutriments et au lessivage des engrais. Cette thèse examine le potentiel du biochar à base de balle de riz en tant qu'amendement durable des sols visant à atténuer les pertes de nutriments, à augmenter le rendement du riz et à améliorer la qualité des grains. Compte tenu de l'abondance des balles de riz au Cambodge et de leur forte teneur en silice, le biochar apparaît comme une solution localement viable pour améliorer la santé des sols. Menée pendant deux ans à l'Institut cambodgien de recherche et de développement agricoles, cette étude comprenait des expériences en colonnes sous serre visant à explorer les interactions entre le biochar et les engrais chimiques sur différentes textures de sol et selon diverses méthodes d'irrigation.

Expérience de la première année : l'étude s'est concentrée sur un seul type de sol afin d'évaluer les effets combinés du biochar issu de la balle de riz et des engrais chimiques sur le lessivage des nutriments et le rendement du riz. Les résultats ont montré que l'application de biochar à raison de 4 t ha^{-1} en association avec des engrais chimiques (CHEM + BIO4) réduisait significativement le lessivage de l'ammonium (NH_4^+) et du nitrate (NO_3^-) par rapport aux engrais seuls, en particulier à partir de la semelle de labour. Cette réduction a été attribuée à la capacité de sorption du biochar. De plus, le traitement CHEM + BIO4 a amélioré le rendement du riz, la biomasse, le nombre de talles, la longueur des panicules, le nombre de grains par panicule et le poids des grains par panicule. Cependant, le biochar n'a pas réduit de manière significative les pertes de phosphate (PO_4^{3-}), ce qui suggère que son efficacité est plus grande pour la gestion de l'azote.

Expérience de deuxième année : le champ d'étude a été élargi pour inclure des sols argileux (S1) et limono-sableux (S2) sous deux régimes d'irrigation, l'inondation continue (CF) et l'alternance humidification-assèchement (AWD). Les traitements comprenaient des engrais chimiques seuls (T1) et en combinaison avec du biochar à 4 t ha^{-1} (T2) et 6 t ha^{-1} (T3). Sur l'ensemble des types de sols et des méthodes d'irrigation, le traitement T3 (CHEM + BIO6) a permis d'obtenir les rendements en grains secs et la teneur en protéines les plus élevés, tout en réduisant de manière significative les pertes de NO_3^-, NH_4^+ et PO_4^{3-}. Bien que la teneur en amylose n'ait pas varié entre les traitements, l'application de biochar a augmenté la biomasse végétale et la teneur en chlorophylle, soulignant son effet positif sur le rendement des cultures.

Dans l'ensemble, les résultats de ces deux années de recherche soulignent que le biochar issu de la balle de riz, en particulier à des doses de 4 à 6 t ha^{-1}, peut améliorer la rétention des nutriments, augmenter le rendement et la teneur en protéines du riz, et favoriser une gestion plus durable de l'eau et des nutriments dans les systèmes rizicoles cambodgiens. Cette recherche vient s'ajouter à un corpus de données de plus en plus important sur le rôle du biochar dans l'agriculture intelligente face au climat. De plus, bien que les deux études démontrent des avantages évidents à court terme, des essais sur le terrain à long terme restent essentiels pour évaluer les impacts durables sur la santé des sols, la stabilité des rendements et la viabilité économique.

សង្ខិត្តន័យ

ស្រូវ គឺជាដំណាំចម្បងសម្រាប់សេដ្ឋកិច្ចកសិកម្ម និងសន្តិសុខស្បៀងអាហារនៅកម្ពុជា។ ដោយឡែក ការដាំដុះស្រូវ តែងតែជួបប្រទះនូវបញ្ហាប្រឈមជាបន្តបន្ទាប់ទាក់ទងនឹងជីជាតិដី ការគ្រប់គ្រងសារធាតុចិញ្ចឹម និងការបាត់បង់សារធាតុចិញ្ចឹមតាមរយៈការជ្រាបតាមស្រទាប់ដី។ សារណាបទនេះ សិក្សាស្រាវជ្រាវអំពីប្រសិទ្ធភាពនៃធ្យូងជីវៈ (Biochar) ដែលផលិតចេញពីអង្កាម ដើម្បីប្រើប្រាស់ជាសារធាតុកែលម្អដីប្រកបដោយនិរន្តរភាព ក្នុងគោលបំណងកាត់បន្ថយការបាត់បង់សារធាតុចិញ្ចឹម ដោយបង្កើនទិន្នផលស្រូវ និងលើកកម្ពស់គុណភាពគ្រាប់អង្ករ។ ជារៀងរាល់ឆ្នាំ ប្រទេសកម្ពុជាផលិតអង្កាមជាច្រើន ហើយអង្កាមទាំងនោះមានផ្ទុកបរិមាណស៊ីលីកា (silica) ខ្ពស់ ដូច្នេះហើយធ្យូងអង្កាម គឺជាជម្រើសមួយដែលសក្តិសមក្នុងការប្រើប្រាស់ដើម្បីថែរក្សានិងបង្កើនគុណភាពដី។ ការសិក្សានេះ ត្រូវបានអនុវត្តរយៈពេលពីរឆ្នាំ នៅវិទ្យាស្ថានស្រាវជ្រាវ និងអភិវឌ្ឍន៍កសិកម្មកម្ពុជា (CARDI) តាមរយៈការពិសោធន៍ក្នុងផ្ទះកញ្ចក់ដោយប្រើប្រាស់បំពង់ពិសោធន៍ ដើម្បីសាកល្បងអំពីអន្តរកម្មរវាងធ្យូងអង្កាម និងជីគីមី នៅលើប្រភេទដី និងវិធីសាស្ត្រស្រោចស្រពផ្សេងៗគ្នា។

ការពិសោធន៍ឆ្នាំទីមួយ៖ ការសិក្សាបានផ្តោតលើប្រភេទដីតែមួយ ដើម្បីវាយតម្លៃពីឥទ្ធិពលរួមគ្នារវាងធ្យូងជីវៈអង្កាម និងជីគីមី ទៅលើការបាត់បង់សារធាតុចិញ្ចឹម និងការលូតលាស់របស់ស្រូវ។ លទ្ធផលបង្ហាញថា ការបន្ថែមធ្យូងអង្កាមចំនួន ៤ តោន/ហិចតា (CHEM + BIO4) ទៅលើជីគីមីបានកាត់បន្ថយការលេចជ្រាបនៃអាម៉ូញ៉ូម (NH_4^+) និងនីត្រាត (NO_3^-) បើធៀបទៅនឹងការប្រើជីគីមីសុទ្ធ ជាពិសេសនៅស្រទាប់ដីដែលភ្ជួររាស់។ សមត្ថភាពរក្សាសារធាតុចិញ្ចឹមរបស់ធ្យូងអង្កាម អាចធ្វើឲ្យមានតំហយចុះនៃការលេចជ្រាបអាម៉ូញ៉ូម (NH_4^+) និងនីត្រាត (NO_3^-) ទៅក្នុងទឹកក្រោមដី ហើយបានធ្វើឲ្យផលស្រូវសរុប ចំនួនកួរស្រូវ ចំនួនគ្រាប់ស្រូវក្នុងមួយកួរ ប្រវែងកួរស្រូវ និងទម្ងន់គ្រាប់ស្រូវក្នុងមួយកួរ កើនឡើងផងដែរ។ ទោះបីជាយ៉ាងនេះក៏ដោយ ធ្យូងអង្កាមក្នុងបរិមាណនេះ មិនមានសមត្ថភាពក្នុងការកាត់បន្ថយការលេចជ្រាបនៃផូស្វាត (PO_4^{3-}) នោះទេ ដែលបង្ហាញថាវាមានប្រសិទ្ធភាពសម្រាប់តែពពួកអាសូតប៉ុននោះ។

ការពិសោធន៍ឆ្នាំទីពីរ៖ វិសាលភាពនៃការសិក្សាត្រូវបានពង្រីកទៅលើប្រភេទដីពីរប្រភេទ នោះគឺប្រភេទដីឥដ្ឋ (S1) និងដីល្បាយខ្សាច់ (S2) ក្រោមវិធីសាស្ត្រស្រោចស្រពចំនួនពីរគឺ ការបញ្ចូលទឹកជាប្រចាំ (Continuous Flooding ឬ CF) និងការបញ្ចូលទឹកឆ្លាស់គ្នា(alternative wetting and drying ឬ AWD)។ បច្ច័យនៃការពិសោធន៍រួមមាន មិនប្រើប្រាស់ជី (T0) ការប្រើប្រាស់ជីគីមីសុទ្ធ (T1) ជីគីមីជាមួយធ្យូងអង្កាម ៤ តោន/ហិចតា (T2) និង ជីគីមីជាមួយធ្យូងអង្កាម ៦ តោន/ហិចតា (T3)។ លទ្ធផលបានបង្ហាញថា ការបន្ថែមធ្យូងអង្កាម ៦ តោន/ហិចតា បានបង្កើនផលស្រូវសរុប និងគុណភាពប្រូតេអ៊ីនក្នុងអង្ករ ចំពោះប្រភេទដី និងវិធីសាស្ត្រស្រោចស្រពទាំងពីរប្រភេទ ហើយវាក៏បានកាត់បន្ថយការបាត់បង់សារធាតុចិញ្ចឹមរួមមាន អាម៉ូញ៉ូម នីត្រាត និងផូស្វាតផងដែរ។ ទោះបីជាធ្យូងអង្កាម មិនបានបង្កើនគុណភាពអាមីឡូសក៏ដោយ ការបន្ថែមវាទៅក្នុងដី បានបង្កើនបរិមាណជីវម៉ាស និងក្លរ៉ូភីល ដែលបង្ហាញពីឥទ្ធិពលវិជ្ជមានលើសមត្ថភាពលូតលាស់របស់ដំណាំស្រូវ។

សរុបមក លទ្ធផលនៃការសិក្សារយៈពេលពីរឆ្នាំនេះបានគូសបញ្ជាក់ថា ការបន្ថែមធ្យូងអង្កាមក្នុងបរិមាណ ៤–៦ តោន/ហិចតា អាចបង្កើនការរក្សាសារធាតុចិញ្ចឹមក្នុងដី បង្កើនទិន្នផលស្រូវ និងកម្រិតប្រូតេអ៊ីន ព្រមទាំងជួយដល់ការគ្រប់គ្រងទឹកនិងសារធាតុចិញ្ចឹមប្រកបដោយនិរន្តរភាពក្នុងប្រព័ន្ធផលិតកម្មស្រូវនៅកម្ពុជា។។ ការស្រាវជ្រាវនេះចូលរួមក្នុងការបន្ថែមភស្តុតាងអំពីតួនាទី និងអត្ថប្រយោជន៍របស់ធ្យូងអង្កាម ក្នុងកសិកម្មឆ្លាតវៃដើម្បីអាកាសធាតុ (climate-smart agriculture) ។ ទោះបីជាការសិក្សាទាំងពីរឆ្នាំបង្ហាញពីអត្ថប្រយោជន៍យ៉ាងនេះក៏ដោយ តែការសិក្សានីមួយៗមានរយៈពេលខ្លី និងមានដែនកំណត់។ ដូច្នេះហើយ ការសាកល្បងលើទីវាលផ្ទាល់ និងរយៈពេលវែងគួរតែធ្វើឡើង ដើម្បីវាយតម្លៃអំពីឥទ្ធិពលនៃធ្យូងអង្កាមនេះ ទៅលើសុខភាពដី ទិន្នផលស្រូវ និងសក្តានុពលសេដ្ឋកិច្ច

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List of Abbreviations

Abbreviations	Definition
ANOVA	Analysis of Variance
ASSET	Agroecology and Safe Food System Transitions
AWD	Alternate Wetting and Drying
CARDI	Cambodian Agricultural Research and Development Institute
CASC	Cambodian Agronomic Soil Classification
CEC	Cation Exchange Capacity
CF	Continuous Flooding
CNTL / T0	Control Treatment (No chemical or biochar)
CSBC	Corn Stover Biochar
EC	Electrical Conductivity
ED	Early-Duration (Rice)
ESP	Exchangeable Sodium Percentage
FAO	Food and Agriculture Organization (of the United Nations)
GBS	Gasification–Biochar Systems
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HSD	Honestly Significant Difference (Post-hoc test)
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
JICA	Japan International Cooperation Agency
LD	Long-Duration (Rice)
MAFF	Ministry of Agriculture, Forestry and Fisheries (Cambodia)
MD	Medium-Duration (Rice)
MoE	Ministry of Environment (Cambodia)
MOWRAM	Ministry of Water Resources and Meteorology (Cambodia)
NCCC	National Climate Change Committee (Cambodia)

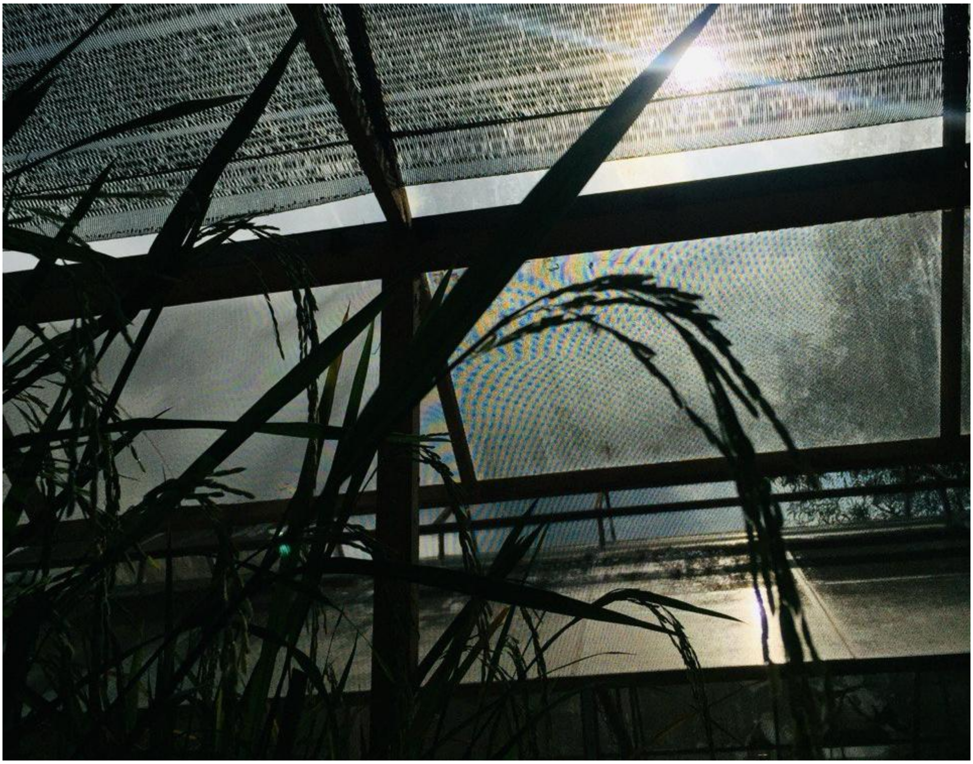
NIS	National Institute of Statistics (Cambodia
NPK	Nitrogen, Phosphorus, and Potassium (Fertilizer)
NUE	Nitrogen Use Efficiency
ODC	Open Development Cambodia
PAHs	Polycyclic Aromatic Hydrocarbons
PCA	Principal Component Analysis
PVC	Polyvinyl Chloride
RHB	Rice Husk Biochar
RHC	Rice Husk Char
SEM	Scanning Electron Microscope
SNP	Sodium Nitroprusside
SOM / OM	Soil Organic Matter
SPAD	Soil Plant Analysis Development (Chlorophyll Meter)
SSA	Specific Surface Area
TKIS	Taing Krasaing Irrigation Scheme
TLUD	Top-Lit UpDraft (Kiln/Stove)
UN-CSAM	United Nations Centre for Sustainable Agricultural Machinery
USDA	United States Department of Agriculture
WRB	World Reference Base for Soil Resources

List of Symbols

Symbols	**Definition**	**Units**
%	Percentage	—
±	Standard deviation / error	—
CEC	Cation Exchange Capacity	$cmol \cdot kg^{-1}$
CH_4	Methane	—
cm	Centimeter	cm
EC	Electrical Conductivity	$dS\ m^{-1}$
$g\ plant^{-1}$	Biomass per plant	$g\ plant^{-1}$
$kg\ ha^{-1}$	Kilograms per hectare	$kg\ ha^{-1}$
N_2O	Nitrous oxide	—
NH_4^+	Ammonium ion	$mg\ L^{-1}$
NO_3^-	Nitrate ion	$mg\ L^{-1}$
pH	Soil acidity/alkalinity	—
PO_4^{3-}	Orthophosphate ion	$mg\ L^{-1}$
R^2	Coefficient of determination	—
SOC	Soil Organic Carbon	%
SPAD	Chlorophyll meter reading (Soil Plant Analysis Development value)	—
$t\ ha^{-1}$	Metric tons per hectare	$t\ ha^{-1}$

Chapter 1

General Introduction



1. Background

1.1. The Significance of rice in Cambodia

Rice serves not only as the staple food of Cambodia but also as a fundamental pillar of its agricultural economy, utilizing about 80% of the nation's cultivated land (Saito et al. 2025). In 2024, the harvested area for rice expanded to 3.71 million hectares, resulting in a yield of 12.79 million metric tons, an impressive increase compared to previous years (MAFF, 2024). This growth can be attributed to better weather conditions and advancements in agricultural technology, which have significantly enhanced productivity and resilience within the sector (Alvar-Beltrán et al. 2022). Rice is cultivated across Cambodia, with several provinces standing out as major producers. The most significant rice-growing provinces include Kampong Thom, Battambang, Prey Veng, Takeo, Kampong Cham, and Banteay Meanchey (Cramb et al. 2020) Figure 1-1.

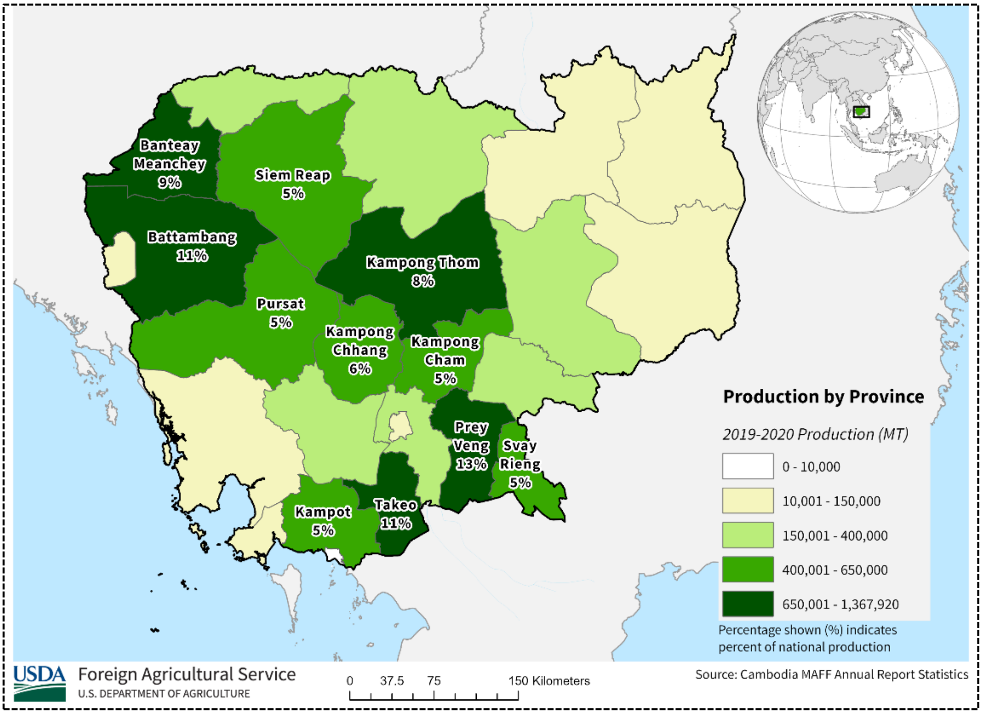


Figure 1-1: Cambodia rice production by province (USDA 2021)

Rice production is a key component of Cambodia's economy, contributing approximately 4.5% to the nation's Gross Domestic Product (GDP) and representing

20% of total household income (Srun and Serey 2024). During the 2024/25 rice season, Cambodia produced 8.47 million tons of rice (milled basis) on 3.86 million hectares. Exports reached 2.5 million tons in calendar year 2024, nearly 50 percent of total milled output, making Cambodia the world's fifth-largest rice exporter. With GDP projected at US$51.39 billion in 2025, rice's 4.5 percent share corresponds to roughly US$2.3 billion in value added (Srun and Serey 2024).

Cambodia has a tropical monsoonal climate, featuring a wet season from June to November and a dry season afterward (Alvar-Beltrán et al. 2022). Annual precipitation and average temperatures are relatively consistent throughout the country. Average annual precipitation ranges from 1400 mm to 4000 mm. While temperatures typically remain between 25°C and 27°C for most of the year, they can exceed 35°C during the summer months (FAO, 2024).

1.2. Rice cultivation practices in Cambodia

Rice cultivation in Cambodia is predominantly based on traditional lowland rainfed systems, which account for the majority of the country's rice production (Saito et al. 2025a; White et al. 2006). Land preparation commonly begins at the onset of the rainy season between May and June. Farmers typically plough the soil using tractors or draft animals, followed by harrowing to break down soil clods and improve puddling conditions for transplanting or direct seeding (Nesbitt 1998). In rainfed lowland systems, fields are generally ploughed one to three times depending on soil conditions, water availability, and management practices (White et al. 2006).

Rice establishment methods in Cambodia include both transplanting and direct seeding. Transplanting is traditionally practiced in lowland areas, where seedlings are first raised in nurseries for approximately 20–30 days before being manually transplanted into puddled fields (Aravindakshan et al. 2024) . However, direct seeding has become increasingly common due to labor shortages, mechanization, and reduced production costs (Chaudhary et al. 2023). Nutrient management practices commonly rely on chemical fertilizers, particularly nitrogen (N), phosphorus (P), and potassium (K), to improve rice productivity. Nevertheless, fertilizer use efficiency is often constrained by poor soil fertility, low organic matter content, and sandy soil textures in many rice-growing regions of Cambodia (Kong et al. 2020a; Seng et al. 2007).

Cambodia commonly cultivates three rice types: long-duration (LD), medium-duration (MD), and early-duration (ED) rice (Saito et al., 2025a). LD rice is mainly grown in rainfed lowland areas and requires approximately six months from seeding

(May–July) to harvest (October–December). MD rice generally has a growth period of about four months and is planted from mid-August for harvest in December. ED rice, introduced more widely since the 2000s, matures within approximately three months, requires less water, and can be cultivated up to three times annually. The cropping cycles include ED1 (January–March), which relies on residual moisture and irrigation; ED2 (May–August); and ED3 (September–December), which depends primarily on wet-season rainfall (Visessri and Heng 2024).

1.3. Soil status and its role in rice cultivation

The Cambodian Agronomic Soil Classification (CASC) categorizes rice-farming soils into 11 distinct groups based on variations in surface properties and physical characteristics (White et al. 2006) (Annex 1). For example, the soil textures in Toul Samroung and Krakor are predominantly clay, whereas Prateah Lang and Prey Khmer exhibit sand dominance (Kong et al. 2020a). Low soil fertility is often attributed to weathering and a lack of organic carbon, a condition frequently observed in Prateah Lang soil, which comprises 25–30% of Cambodia's rice-growing area. In contrast, loamy or clay-rich soils such as Toul Samroung (7–10% of the rice-growing area), Bakan (10–15%), and Krakor (15%) are associated with the potential for high productivity in rice cultivation (Kong et al. 2020a).

When aligned with international frameworks, CASC groups can be directly linked to the WRB soil types represented on the national soil map (Figure 1-2). For example, Prey Khmer soils correlate with Crocker’s Red-Yellow Podzols and are classified as Dystric Fluvisols or occasionally Arenosols under WRB, reflecting their sandy texture and low fertility. Prateah Lang soils, which are often immature gley soils found on poorly drained terraces, correspond to Gleysols in WRB, highlighting their hydromorphic nature and the constraints they pose for rice cultivation. Bakan soils, identified locally as gray hydromorphs, are generally classified as Luvisols, though they may also fall into Planosols or Acrisols depending on drainage conditions and horizon development. Meanwhile, Toul Samroung and Krakor soils, characterized by clay-rich profiles, align with Vertisols and Luvisols. These soil types are particularly favorable for rice production due to their high water-holding capacity and strong nutrient retention (White et al. 2006).

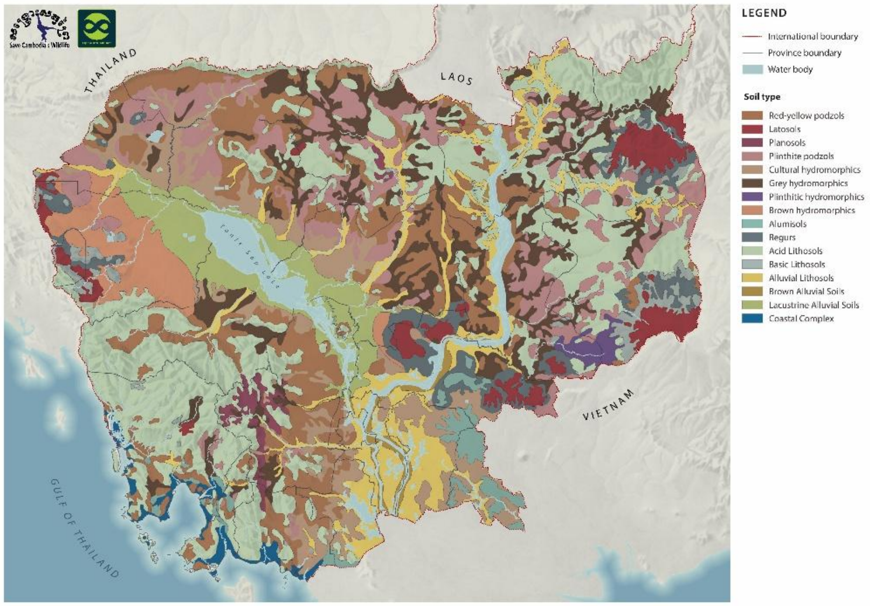


Figure 1-2: Distribution of soil type in Cambodia (adapted from Open Development Cambodia, 2025; original soil classification based on Crocker, (1962))

The earliest systematic survey of Cambodia's soils was carried out by Crocker, (1962) in his *Exploratory Survey of the Soils of Cambodia*. Since then, most soil studies have been conducted sporadically, resulting in a fragmented database of uneven quality (White et al. 2006). Crocker's classification itself has seen limited practical use among agronomists, largely because of the coarse scale of his maps and the difficulty non-specialists face in identifying soil units in the field. The WRB framework, combined with CASC, now offers a more practical bridge between local agronomic knowledge and international soil science standards.

Sand-textured surface horizons (15-40 cm depth) cover much of Cambodia, with deep sands also prevalent. Effective management of these soils is crucial for sustainable agriculture (Seng et al. 2007). The abundance of siliceous Mesozoic sedimentary rocks largely explains the presence of sands in the region. However, the diversity of sandy soils and their formation factors remain underexplored. Limited knowledge exists regarding their edaphic properties, particularly those affecting agricultural productivity.

Soil texture significantly impacts plant growth and nutrient uptake, with clay-dominant soils generally more fertile due to higher organic matter content compared to sandy soils (Adeniji et al. 2025). Soil compaction increases bulk density, reducing porosity and aeration, which can hinder root growth and nutrient availability (Dexter 2004; Rosolem et al. 2002). Global intensive agriculture has favored use for short-term profits, which can lead to soil degradation (Behera and France 2016; Shah et al. 2017). Although tillage operations aim to enhance soil structure, excessive use can result in further compaction (Hasanuzzaman 2019).

1.4. Irrigation practices in Cambodia

In Cambodia, around 821,000 household agricultural holdings (44% of all holdings) use some form of irrigation, with the highest adoption in the plains (58%) and the lowest in the coastal zone (26%). On average, 64% of the irrigated area is actively cultivated. Households not using irrigation cite reasons such as viewing it as unnecessary (67%), lack of water (22%), or affordability issues (11%) (NIS 2023a). As access to canal water increases, rice farmers are investing more in their fields during the dry season to improve productivity. Despite abundant water resources from the Mekong River and Tonle Sap Lake, many areas lack developed irrigation infrastructure, leading to reliance on seasonal rainfall and inconsistent yields (ADB 2021)

Government initiatives and international aid aim to expand irrigation networks and enhance agricultural productivity. Furthermore, community-based irrigation management is gaining importance, as it empowers local farmers and optimizes water distribution. With over 506,000 hectares of lowland irrigation systems supporting rice across 15 provinces, efforts are underway to expand groundwater irrigation in some regions (NIS 2023a). Traditional methods rely on gravity-fed systems, while the use of hand-held tractors is increasing. In flood-prone areas, deep-water rice systems allow cultivation of varieties that grow between 2 to 6 meters tall (da-Silva-Branco et al. 2026).

Between 2015 and 2016, droughts led to reduced rainfall, warmer temperatures, and delayed or shortened monsoon seasons, affecting approximately 2.4 million people. According to the National Climate Change Committee (NCCC 2013), Cambodia's average surface temperature has increased by 0.8°C since 1960. The IPCC's Sixth Assessment Report (2023) forecasts that Southeast Asia, including Cambodia, will experience a temperature rise of 1.5°C to 2.5°C by 2050 compared to pre-industrial levels (1850–1900), with the most significant warming anticipated during the dry season. The report also anticipates more frequent and intense heatwaves, as well as increasingly severe rainfall events. The primary crop cultivated in the region is rainfed lowland rice, which makes up the majority of rice cultivation (Tsujimoto et al. 2018). This type of rice is primarily cultivated by smallholder farmers who rely on seasonal rainfall and traditional farming practices. However, these farmers often encounter challenges, such as high-cost production and climate variability, which can significantly affect their yields and food security (Sithirith et al. 2024).

1.5. Introduction to water-saving method

Although Cambodia has abundant water resources from the Mekong and Tonle Sap, irrigation infrastructure remains uneven, and farmers often rely on seasonal rainfall. Climate variability, including droughts and delayed monsoons, has intensified the need for more efficient water management. Against this backdrop, Alternate Wetting and Drying (AWD) has emerged as a climate-smart irrigation technique designed to save water while sustaining yields. AWD involves allowing the rice field to dry to a certain threshold before re-flooding, rather than maintaining continuous standing water. This cycle reduces water use by 15–30% compared to traditional flooding, while maintaining or even improving yields.

Research conducted by the International Rice Research Institute (IRRI) and the Food and Agriculture Organization (FAO) across Asia shows that Alternate Wetting and Drying (AWD) not only conserves water but also helps mitigate climate change by reducing methane emissions from rice paddies (IRRI 2023). Farmers who adopt AWD often report lower pumping costs and increased resilience during dry seasons (Lampayan et al. 2015).

However, the adoption of AWD in Cambodia is still limited due to concerns about potential yield losses, inadequate extension training, and infrastructure constraints (Phoeurn et al. 2025). Recent pilot projects under the Agroecology and Safe Food System Transitions (ASSET) initiative and the WAT4CAM program highlight both the potential benefits and the challenges of scaling AWD in Cambodian rice systems. Currently, irrigation practices in the region primarily rely on gravity-fed canals and rainfall, which means AWD remains underutilized, despite its relevance in areas with increasing access to groundwater or canal systems.

The AWD system is structured around three main components: (1) maintaining a thin layer of 2–3 cm of standing water from panicle initiation to the end of flowering, when rice is most sensitive to water deficit; (2) shallow flooding during the first two weeks after seeding or transplanting to aid seedling recovery and suppress weeds; and (3) alternating wetting and drying cycles during all other growth stages (Mubeen and Jabran 2019). Thresholds for initiating AWD can be determined through six indicators: soil water potential, a set number of days without flooding, visible soil cracks, plant stress symptoms, field water level dropping to a specific depth, or ditch irrigation practices (Nalley et al. 2015). By regulating water inputs in this way, AWD ensures rice's physiological needs are met while significantly reducing total irrigation demand

1.6. Fertilization practice in Cambodia

Long-duration rice varieties are favored for their high quality and strong consumer demand, although access to modern varieties, fertilizers, and chemical pesticides has increased in recent years (Prom-u-thai and Rerkasem 2020). Future increases in crop production are expected to primarily stem from enhanced farm yields, with fertilizers remaining crucial to support crop intensification. To enhance the role of fertilizers in transforming agriculture for food security, agricultural growth, and export promotion, it is essential to address the factors that restrict the fertilizer market.

Cambodia's fertilizer supply was historically dependent on imports from Vietnam and Thailand, which surged after 1996 to support agricultural intensification. In recent years, however, domestic blending and distribution facilities have been established, supplying urea, DAP, and NPK products to farmers across the country. As a result, Cambodia's fertilizer market now reflects a mix of imports and local production, undergoing rapid evolution to meet the demands of farmers. In 2011, Cambodia imported approximately 433,120 tons of NPK fertilizer products, a significant increase from 137,877 tons in 2002, and this trend continues to rise annually (Theng et al. 2014). In 2023, Cambodia imported 1,048,820 tons of commercial fertilizers under HS 3101 ("Animal or vegetable fertilizers") (World Bank, 2023). The previous outdated report also showed that many Cambodian farmers are still using inadequate techniques for soil management and irrigation in rice cultivation. Common issues include the insufficient or excessive use of fertilizers, poor erosion control maintenance, and reliance on heavy machinery (Ly et al. 2012). Compared to neighboring countries, another factor contributing to low rice yields in Cambodia is the fertilization technique (Theng et al. 2014), despite numerous demonstration trials illustrating a positive yield response to fertilizer applications (Bijay-Singh and Singh 2017). This challenge persists in the diverse and uncertain environments of Cambodia's rainfed rice-growing regions.

1.7. Nutrient leakage and environmental concern

Chemical fertilizers are widely used to boost crop yields by supplying concentrated nutrients, particularly nitrogen (N) and phosphorus (P), which are often growth-limiting in rice systems (Rashmi et al. 2017a). However, excessive application frequently exceeds crop demand, leading to nutrient leaching and runoff. Nitrate (NO_3^-), due to its high solubility and mobility, is especially prone to leaching below the root zone, while phosphorus can accumulate in soils and contribute to long-term eutrophication risks (Rashmi et al. 2017b).

Leaching losses are most severe in coarse-textured soils with low cation exchange capacity, such as sandy soils common in Southeast Asia, where nutrients move rapidly through the profile (Laird et al. 2010). Elevated nitrate concentrations in groundwater have been linked to health risks including methemoglobinemia in infants (Chaudhary et al. 2025), while phosphorus runoff drives harmful algal blooms and oxygen depletion in aquatic ecosystems (Ward et al. 2018). Globally, inefficient fertilizer use is estimated to waste 40–60% of applied nitrogen, representing both economic losses for farmers and environmental damage (Bhatt et al. 2025). Recent meta-analyses confirm that nitrogen recovery efficiency in rice rarely exceeds 50%, underscoring the scale of nutrient losses (You et al. 2023).

To mitigate nutrient losses, sustainable soil and water management strategies are essential. Optimizing fertilizer rates and timing to match crop demand, adopting water-saving irrigation practices such as alternate wetting and drying (AWD), and applying soil amendments like biochar have all shown promise. Biochar, in particular, has been demonstrated to increase nutrient retention and reduce nitrate leaching in sandy soils by enhancing cation exchange capacity and water holding capacity (Gelardi et al. 2021). Long-term field trials in Asia also report that biochar can improve nitrogen use efficiency and reduce greenhouse gas emissions in flooded rice systems (Ballester et al. 2021a; Jeffery et al. 2011) . These practices can help regions such as Cambodia balance the urgent need for higher rice yields with long-term ecological sustainability.

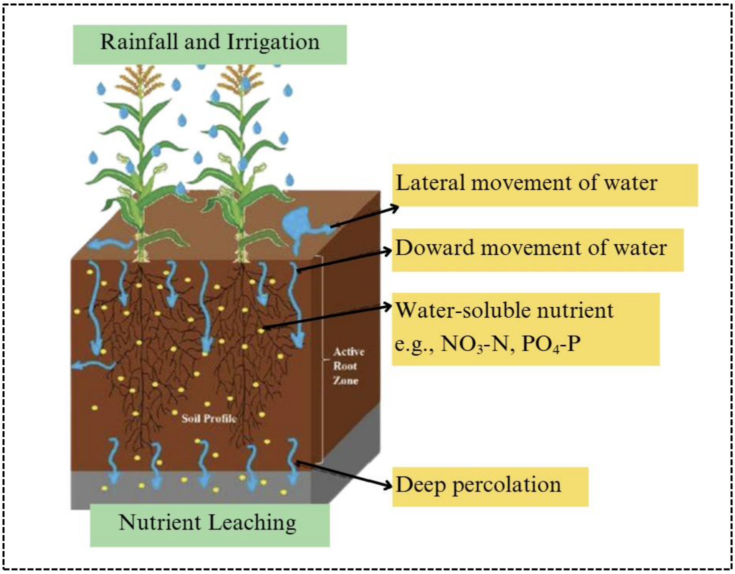


Figure 1-3: Schematic representation of nutrient leaching in the soil profile (Acharya et al. 2023)

1.8. Introduction to soil column experiment

Soil column experiments are widely recognized as a valuable tool in agronomy and environmental science because they allow researchers to simulate soil processes under controlled conditions (Ikoyi and Schmalenberger 2021a). Unlike field trials, which are influenced by variability in climate, management, and landscape, soil columns provide a standardized environment to study water movement, nutrient leaching, and soil–amendment interactions. This makes them particularly useful for investigating mechanisms that are difficult to isolate in the field, such as the role of soil structure in nutrient retention or the effect of irrigation regimes on water dynamics (Gunal 2025a). Controlled column studies have been used recently to demonstrate how biochar alters nutrient distribution and reduces leaching under simulated rainfall or irrigation events (Gunal 2025b).

A key distinction in soil column research lies between undisturbed and disturbed conditions. Undisturbed columns preserve natural soil structure, pore networks, and layering; they therefore capture realistic flow paths, preferential flow, and the interaction of amendments with intact aggregates (Powelson et al. 2023). Disturbed columns (homogenized soils) remove structural heterogeneity and are useful for isolating chemical processes such as adsorption, pH buffering, and cation exchange. (Gelardi et al. 2021).

2. Introduction to biochar

2.1. *What is biochar?*

Biochar is a carbon-rich byproduct that is produced when biomass, such as plant residues, wood, or agricultural waste is heated through the process of pyrolysis in an oxygen-depleted environment (Singh et al. 2025). It can be produced from all sorts of biomass residues under various pyrolytic conditions, and thus it can have varying chemical and physical properties. Biochar contains organic material with a composition varying from barely pyrolysed lignin at low temperatures to a highly carbonized material at high temperatures and coke that has been formed by reaction of volatile components (Almutairi et al. 2023). Producing biochar requires less energy and cost than active carbon generation since biochar is generally obtained at lower temperatures and without additional activation processing. It consists primarily of cellulose, hemicellulose, and lignin (Sun et al. 2025).

2.2. *Key properties of biochar*

Biochar's pore structure and surface area are influenced by a variety of factors, including the type of feedstock used, the rate at which it is heated during pyrolysis, the size of the particles, the content of ash, and any activation processes applied (Tomczyk et al. 2020). Among these, the pyrolysis temperature emerges as the most critical factor. The temperature at which pyrolysis occurs can significantly affect the decomposition of organic material, leading to variations in the physical and chemical properties of the resulting biochar (Uroić Štefanko and Leszczynska 2020). Higher pyrolysis temperatures typically enhance the development of porosity and surface area, making biochar more effective for applications such as soil amendment and carbon sequestration (Khater et al. 2024). Understanding the interplay between these factors is essential for optimizing biochar production to meet specific agricultural and environmental goals.

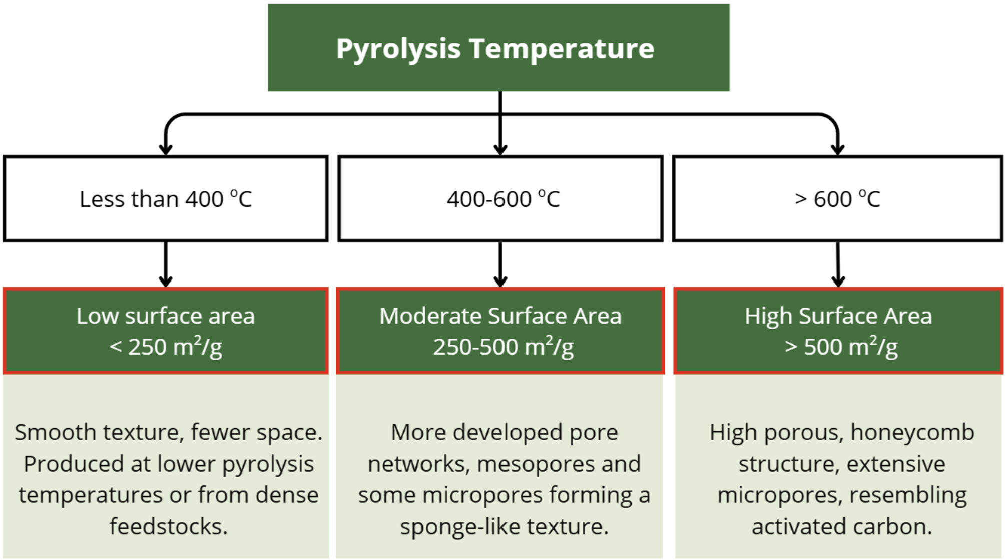


Figure 1-4: Biochar surface area and properties, adapted from (Ghorbani et al. 2022)

Biochar is a versatile and cost-effective carbonaceous material that has gained significant attention for its various environmental applications (Biswal and Balasubramanian 2025). Its adaptable physicochemical properties, such as surface area and pore size, contribute to its remarkable adsorption capacity and chemical stability. These characteristics make biochar an effective solution for mitigating greenhouse gas emissions and replacing traditional fossil carbon carriers in various processes (Rubin et al. 2020).

When investigating the removal of specific contaminants or components through adsorption, the selection of the appropriate adsorbent material is a critical step that can greatly influence the effectiveness of the process. In this context, biochar's performance is particularly affected by its porous structure, which provides a large surface area for adsorption, as well as the presence of functional groups on its surface. These functional groups can enhance interaction with trace elements, thereby improving their adsorption efficiency (Zoroufchi Benis et al. 2023).

Overall, the unique properties of biochar not only promote its use in environmental applications but also highlight its potential to serve as a sustainable alternative in managing pollution (Afshar and Mofatteh 2024). When applied to soil, biochar’s porous structure and surface functional groups enhance nutrient retention, water-holding capacity, and microbial activity (Mensah et al. 2025a). This not only improves soil fertility and crop productivity but also contributes to long-term carbon sequestration and sustainable land management.

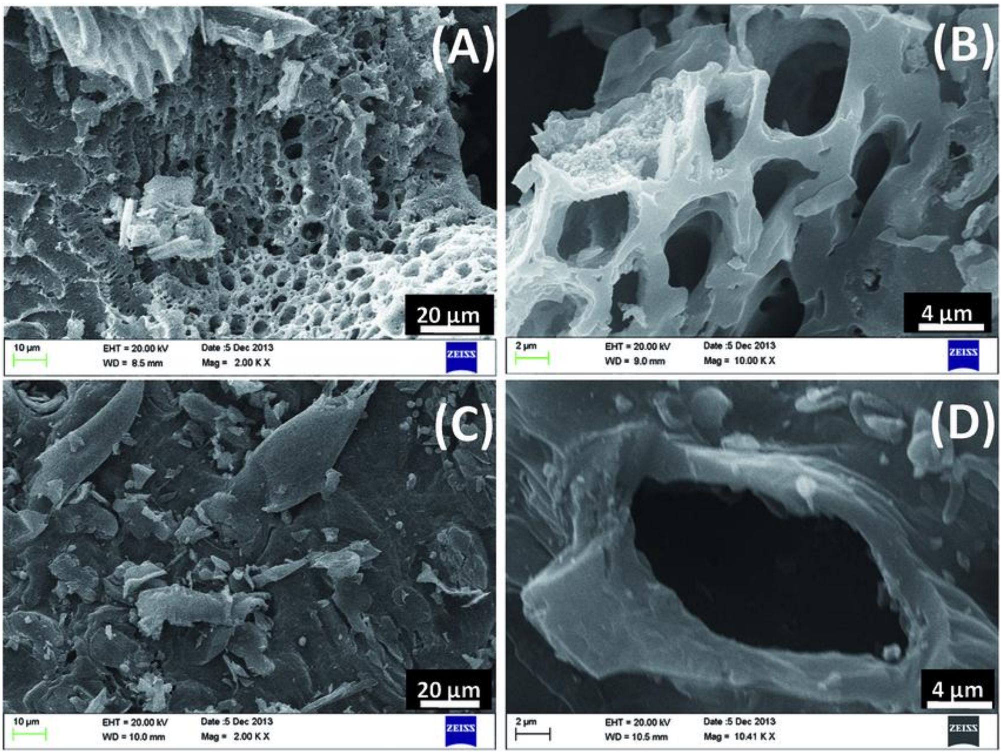


Figure 1-5: SEM micrographs of rice husk biochar (RHBC) at (A) 2KX (B) 10KX and corn stover biochar (CSBC) at (C) 2KX (D) 10.41KX magnifications (Mohan et al. 2018).

Because of its adaptable physicochemical properties, high adsorption capacity, and chemical stability, biochar has been widely studied as a soil amendment to improve nutrient retention (Dayoub et al. 2024). In agricultural systems, its porous structure and functional groups can adsorb ammonium, nitrate, and phosphate, reducing nutrient leaching losses and enhancing fertilizer use efficiency (Singh et al. 2025). These properties make biochar particularly relevant for sandy soils in Cambodia, where nutrient mobility and groundwater contamination are major concerns.

2.3. *Biochar soil application: the global research*

The reaction states of biochar in soil include dissolution (1–3 weeks), reactive surface development (1–6 months), and aging (beyond 6 months) (Joseph et al. 2021).

In the initial stage, soluble organic and mineral compounds are released through biochar pores, increasing dissolved organic carbon, cations, and anions in the soil solution. As biochar interacts with plant roots and microorganisms, its porous structure and functional groups (e.g., carboxyl, carbonyl, hydroxyl) adsorb nutrients and influence microbial activity. In the long term, biochar undergoes aging through fragmentation and surface oxidation, further altering its capacity to retain nutrients and improve soil structure (Tang 2025).

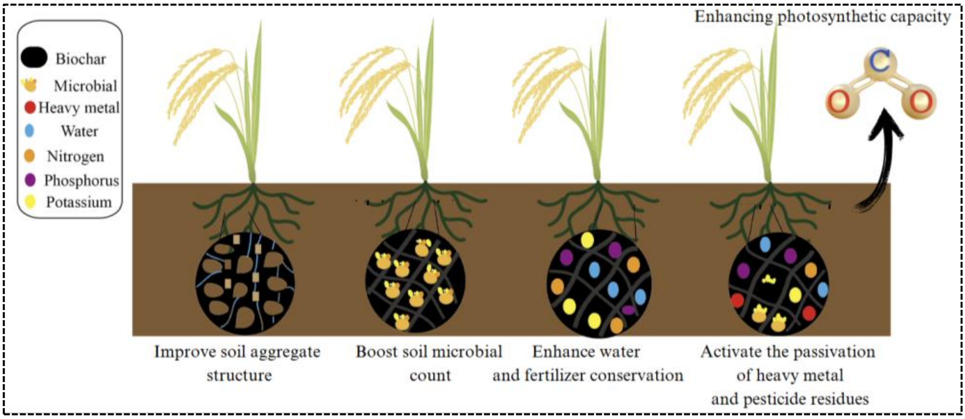


Figure 1-6: Biochar activity in soil, adapted from Xu et al. (2023)

2.3.1. Reduce nutrient loss

One of biochar's critical environmental benefits is its ability to serve as a nutrient sorbent, minimizing nitrogen and phosphorus loss from agricultural soils (Vejan et al. 2021). Studies indicate that biochar characteristics, particularly its surface charge and porosity, greatly influence its nutrient sorption capability. Studies have shown that biochar, due to its surface area and charge, can act as an environmental sorbent (Afshar and Mofatteh 2024). However, a single type of biochar may not be suitable for all substances. Research on the sorption and release of ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}) by independent biochar has been limited. Previous studies indicate that biochar's sorption affinity varies significantly based on its characteristics and the nutrient type (Sun et al. 2025). For instance, (Yao et al. 2012) found that nitrate is primarily adsorbed onto high-temperature biochar, while cation exchange capacity (CEC) is key for ammonium adsorption, with no definitive trend for phosphate sorption or release.

The interaction between biochar and soil affects nutrient leaching and retention, influenced by biochar and soil properties (Omokaro et al. 2025a). Studies show that coconut husk biochar produced at 700 °C reduced 47.46 % NO_3^--N leaching and 29.13 % TN leaching, which achieved the highest NO_3^--N leaching reduction among all the tested biochar (Liang et al. 2025). High-temperature biochar is particularly effective in adsorbing nitrate because pyrolysis at elevated temperatures increases aromaticity, surface area, and the abundance of oxygen-containing functional groups that enhance anion retention (Hailegnaw et al. 2019). Its cation exchange capacity (CEC), which develops during biochar aging, is crucial for ammonium retention, as positively charged ammonium ions are held on negatively charged sites.

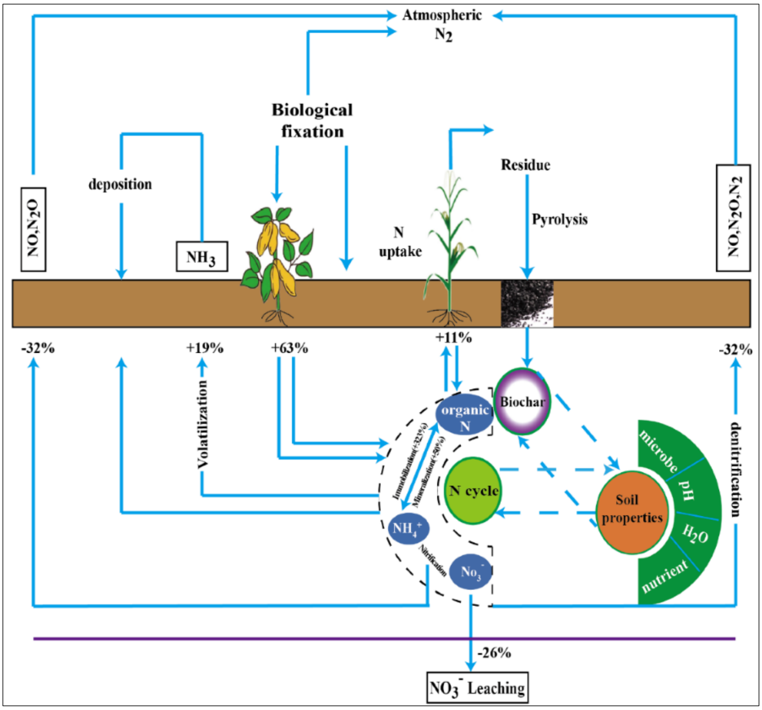


Figure 1-7: How does biochar influence soil N cycle (Liu et al. 2018)

Biochar can also reduce phosphorus loss by enhancing phosphate adsorption and decreasing phosphorus mobility in soil. The effectiveness of phosphorus retention depends largely on the mineral composition and ash content of the biochar (Kumari et al. 2025). In addition, the porous structure of biochar can improve phosphorus retention by increasing soil adsorption sites and reducing nutrient runoff. Several studies have reported that biochar application decreases dissolved phosphorus losses while simultaneously improving phosphorus availability for plant uptake under acidic or nutrient-deficient soil conditions (Vejan et al. 2021; Yao et al. 2012). These findings suggest that biochar has considerable potential to mitigate both nitrogen and phosphorus losses in agricultural systems. Phosphate sorption, however, remains more complex, as it depends strongly on feedstock type, pyrolysis temperature, and the presence of mineral phases such as calcium, magnesium, or iron oxides (Kumari et al. 2025). Some studies report enhanced phosphate retention in biochars rich in ash content, while others show limited sorption or even release under certain soil conditions (Yao et al. 2012).

2.3.2. Enhanced Water-Use Efficiency

Biochar significantly enhances water retention and management in soils through its porous structure, which increases soil porosity and moisture availability for plants (Mohammadi et al. 2017). It promotes soil particle stability, reducing water runoff and improving infiltration. Additionally, biochar enhances capillary action and hydraulic conductivity, ensuring even water distribution for plant access (Jia et al. 2024). By creating a protective layer over the soil, it minimizes evaporation losses and retains more water. With a high cation exchange capacity, biochar also retains essential nutrients, improving plant water use efficiency (Omokaro et al. 2025a). Furthermore, it supports beneficial microbial activity that enhances soil structure and moisture retention while lowering the permanent wilting point, allowing plants to extract water more effectively even in drought conditions (Joseph et al. 2021). Overall, biochar plays a crucial role in improving water management and supporting plant health.

2.3.3. Enhanced plant growth and yield

The application of biochar has demonstrated positive effects on crop growth and yield, attributed to its ability to enhance soil structure, optimize fertilization efficiency, and regulate nutrient availability (Singh et al. 2022) . Studies show that biochar reduces nutrient loss, increasing nutrient accessibility to plants, boosts plant biomass and grain weight per panicle by improving root development and nutrient uptake, enhances rice tiller number and panicle formation, contributing to higher yield potential (Khan et al. 2024; Yin et al. 2021).

Significant improvements in rice yield and quality content have been reported following biochar applications at optimized rates (Chen et al. 2023a). However, the effectiveness of biochar varies based on application rate, soil type, and irrigation method. It is essential to refine biochar usage strategies to maximize its benefits while ensuring long-term soil sustainability.

Table 1-1 : Example of biochar for soil application research in the global

Author (Year)	Region	Focus	Key Findings
Yang et al. (2024)	Northeast China	Biochar + rice straw return	Improved soil organic carbon, enhanced rice yield despite cold climate constraints.
Shyam et al. (2025)	India	Soil quality & nutrient retention	Biochar improved soil structure, reduced nutrient leaching, enhanced microbial activity.
Bekchanova et al. (2024)	Nigeria	Sandy soils, nutrient retention	Biochar decreased nitrate loss by 23% and phosphate loss by 37%, improved fertility.
Rubin et al. (2020)	USA (Wetlands)	Nutrient leaching & GHG emissions	Biochar reduced NO3- leaching by 92% and PO43- by 63%. Most effective in soils with episodic flooding and drying.
Jeffery et al. (2011)	Europe	Crop yield response	Average yield increase of ~10% across crops; strongest effects in degraded soils.
Li et al. (2019)	Global (Meta-analysis)	Phosphorus availability	Synthesized 124 studies; biochar increased soil P availability by 45% and plant P uptake by 48%, especially in acidic and neutral soils.
Agegnehu et al. (2016)	Ethiopia (Tropical Soil)	Biochar, compost, and co-composted biochar	Increased soil organic carbon (SOC) and maize yield (up to 29%), while improving water-holding capacity and reducing GHG emissions.
Phuong et al. (2020)	Mekong Delta, Vietnam	Rice husk biochar + compost in saline fields	Reduced soil bulk density and salinity (ESP); significantly increased soil porosity and available Phosphorus.

2.4. *Drawback of biochar soil application*

While biochar has numerous benefits in soil applications, there are also notable drawbacks to consider (Kamali et al. 2022). One significant concern is the potential for nutrient immobilization, where biochar can temporarily bind essential nutrients, such as nitrogen, making them less available to plants in the short term (Kocsis et al. 2022). This phenomenon may lead to initial reductions in crop yields, particularly if the biochar is applied in large quantities or without adequate nutrient management practices (Lin et al. 2025). Additionally, the variability in biochar properties, influenced by feedstock type and pyrolysis conditions, can result in inconsistent performance across different soils and environmental conditions (He et al. 2024). Furthermore, the long-term effects of biochar application on soil microbiomes are not fully understood, and there is a possibility that it could alter microbial populations in ways that are detrimental to soil health. Finally, there are concerns regarding the potential leaching of hazardous compounds present in some biochar types, which could contaminate groundwater (Dong et al. 2025). Therefore, careful consideration of these factors is essential when integrating biochar into soil management practices.

2.5. *Type of biochar feedstock*

The production of biochar is influenced by a variety of feedstocks and pyrolysis conditions, resulting in different types of biochar, each with distinct characteristics and applications (Tomczyk et al. 2020). For example, wood-based biochar is recognized for its high carbon content and structural stability, making it particularly effective for soil amendment and carbon sequestration (Boraah et al. 2023). Conversely, agricultural waste biochar, which comes from crop residues like straw and husks, is rich in nutrients that enhance soil fertility while also promoting waste reduction (Rex et al. 2023).

Manure-based biochar, created from livestock waste, not only retains essential nutrients but also boosts soil microbial activity, benefiting crop growth (Rathnayake et al. 2023). Additionally, biochar derived from municipal solid waste can assist urban areas by managing organic refuse and delivering environmental advantages (Razzak 2024).

The properties of each type of biochar, including surface area, porosity, and nutrient content, can vary significantly, enabling tailored applications for specific agricultural or environmental needs. Therefore, understanding the diverse types and characteristics of biochar is essential for optimizing its effectiveness in a variety of contexts. Among these sources, rice husk stands out as a widely available agricultural byproduct with diverse applications. Accounting for approximately **20% of the rice grain's weight**, rice husk is the protective outer layer that is removed during milling (Vijaya et al. 2025).

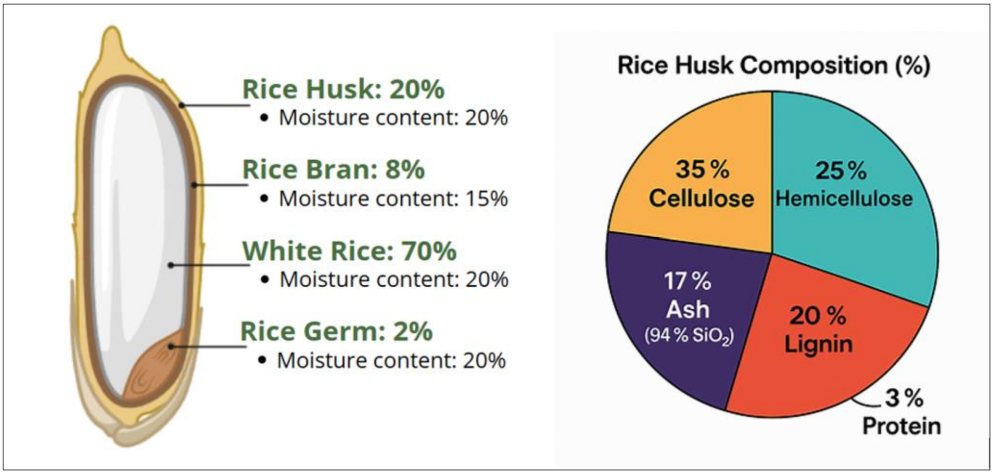


Figure 1-8: Composition of rice grain and rice husk (Nnadiukwu et al. 2023)

One of the defining features of rice husk is its high silica content (16-22%), which makes it highly resistant to decomposition and enhances its durability (Arshad and Moin 2025). Composed of cellulose, hemicellulose, and lignin, rice husk has excellent potential as a feedstock for biochar production, contributing to carbon sequestration and soil health improvements.

3. Biochar status in Cambodia

3.1. Rice husk availability in Cambodia

Rice husk is considered an attractive feedstock for biochar production in Cambodia due to its large availability, low economic value (in peak season), and high silica content. Rice milling typically generates rice husk as a byproduct at approximately 20% of the total grain weight, resulting in substantial annual biomass production in major rice-producing provinces (Pode et al. 2015).

Perspective: Large commercial rice mills commonly utilize rice husk as a biomass fuel for boilers and rice dryers, allowing them to reduce dependence on diesel or electricity and lower operational costs. In some cases, excess rice husk is sold to cement factories, brick kilns, or biomass energy facilities. On the other hand, smaller rice mills often lack sufficient infrastructure for efficient husk utilization and may dispose of rice husk through open burning, dumping, or low-value applications such as animal bedding. Rice mills are distributed throughout Cambodia; however, large-scale commercial rice mills are predominantly concentrated in major rice-producing provinces such as Battambang, Kampong Thom, Banteay Meanchey, and several other key agricultural regions. These areas function as important rice production and processing hubs due to their extensive cultivation areas and strong connections to domestic and export markets.

However, a growing number of registered businesses and family enterprises are shifting toward biochar production, recognizing its value as a soil amendment and carbon sequestration solution. While this emerging trend reflects increasing interest in sustainable agricultural practices, producers still face challenges in optimizing conversion rates and scaling production. Addressing these gaps through targeted studies and technological advancements could significantly enhance the efficiency and adoption of rice husk biochar in the region.

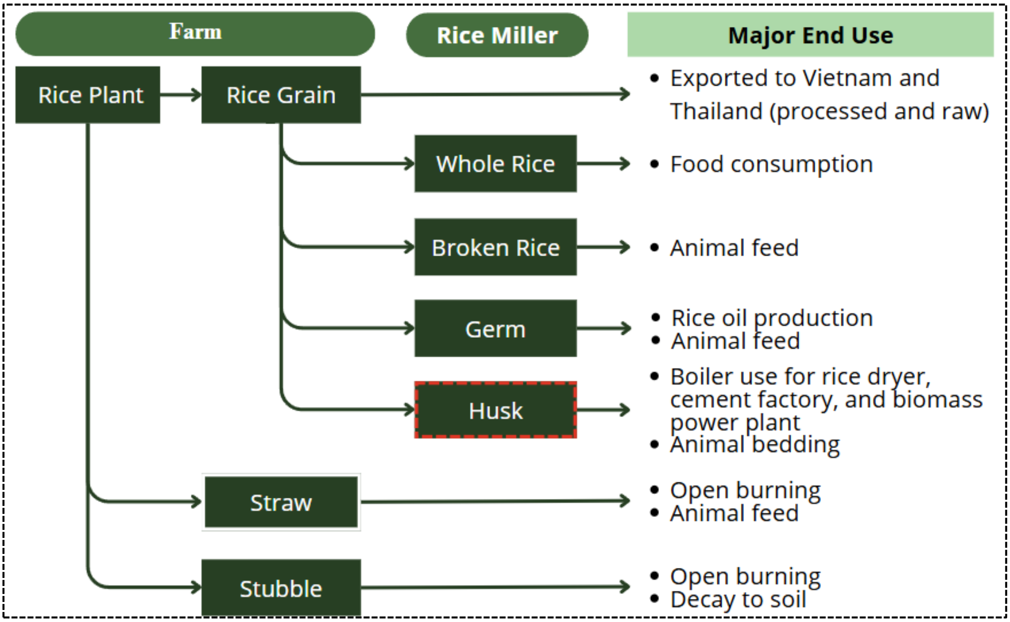


Figure 1-9: The flow of rice husk biomass feedstock processing, adapted from (Nam et al. 2025) and an unofficial survey from Midori Climate Partner Pte.

3.2. Biochar production facilities in Cambodia

In Cambodia, the production of biochar is experiencing a gradual evolution, merging traditional methods with modern technologies (Green 2025) Figure 1-10. In rural areas, traditional practices such as open burning and the use of simple clay or metal kilns remain prevalent due to their accessibility and low cost (Chan 2020). However, these methods often result in inefficient carbon retention and high emissions, which restrict their environmental advantages (Cornelissen et al. 2016).

Recent efforts by NGOs, researchers, and farmer cooperatives have introduced improved pyrolysis systems tailored to local conditions. These include modified kilns with enhanced airflow control, top-lit updraft (TLUD) units, and small-scale retort designs that offer cleaner combustion and higher-quality biochar. Community-based pyrolysis initiatives are gaining traction, enabling farmers to convert agricultural residues like rice husk, coconut shells, and cassava stems into valuable soil amendments while addressing waste management challenges. Although advanced pyrolysis machines with controlled temperature and oxygen levels are still limited in rural deployment, pilot projects have demonstrated their potential to maximize carbon sequestration and produce consistent biochar.

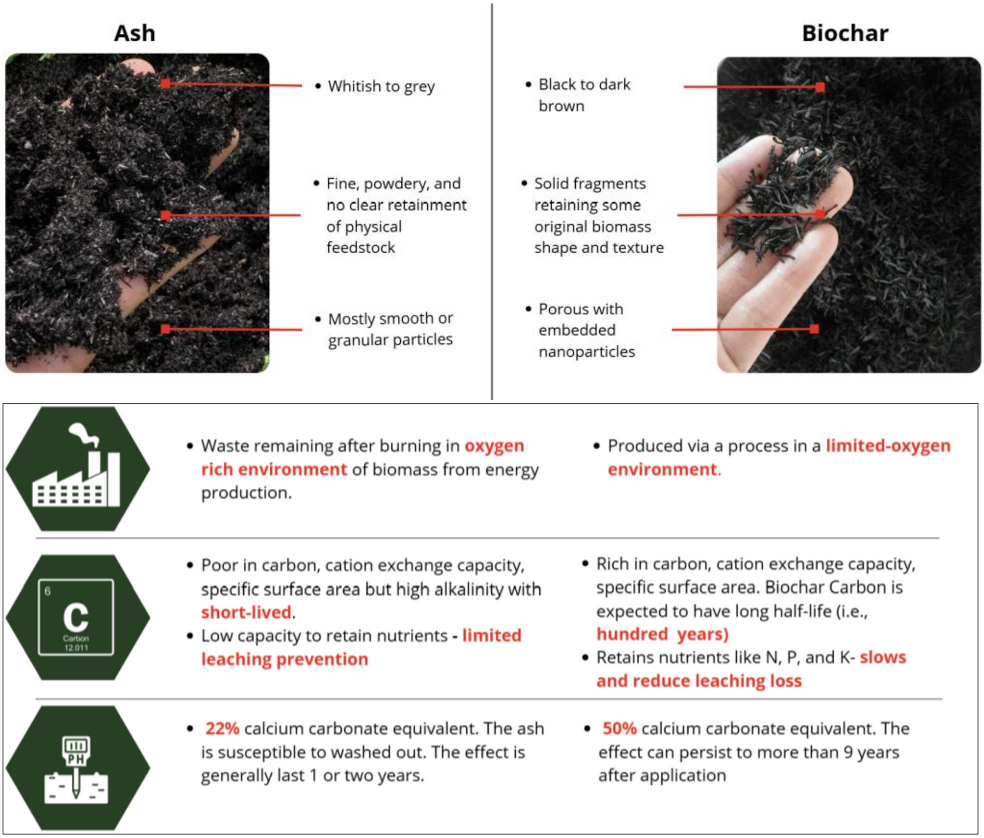
As awareness of biochar's agronomic and environmental benefits grows, expanding access to appropriate technologies and providing training for local producers will be essential to enhance sustainability, soil health, and climate resilience in Cambodia's agricultural sector.

Various traditional agricultural practices, such as applying rice husk charcoal and various kinds of ash as soil amendments and mineral supply, have been developed since ancient times in Asian countries, in which rice husk charcoal has been regarded as one of the most common soil amendments (Singh Karam et al. 2022a) . However, that evidence has long been hidden. Limited-resource farmers can easily process biochar derived from fallow vegetation or organic wastes. Converting local biomass into biochar can reduce input costs and improve soil fertility.

Figure 1-10: Biochar production facility types available in Cambodia (MAFF, 2025)

3.3. Biochar and ash confusion

In Cambodia, there is a notable confusion between biochar and ash, which stems from a lack of understanding about their distinct properties and benefits. While both are byproducts of biomass, biochar is produced through the pyrolysis of organic materials under controlled conditions, leading to a stable form of carbon that enhances soil fertility, water retention, and microbial activity. In contrast, ash is the residual material left after the complete combustion of organic matter, which typically has a lower nutrient content and lacks the structural benefits of biochar. This misunderstanding has been documented in farmer surveys and extension reports, where rice husk charcoal and ash are often used interchangeably. Such confusion hinders the adoption of biochar as a sustainable amendment, underscoring the need for targeted education and demonstration projects to highlight biochar's agronomic and climate benefits.



Ash	Biochar
Waste remaining after burning in **oxygen rich environment** of biomass from energy production.	Produced via a process in a **limited-oxygen environment**.
Poor in carbon, cation exchange capacity, specific surface area but high alkalinity with **short-lived**. Low capacity to retain nutrients - **limited leaching prevention**	Rich in carbon, cation exchange capacity, specific surface area. Biochar Carbon is expected to have long half-life (i.e., **hundred years)** Retains nutrients like N, P, and K- **slows and reduce leaching loss**
22% calcium carbonate equivalent. The ash is susceptible to washed out. The effect is generally last 1 or two years.	**50%** calcium carbonate equivalent. The effect can persist to more than 9 years after application

Figure 1-11: Key difference between biochar and ash, adapted from (Chojnacka et al. 2025)

3.4. Biochar Market and Price in Cambodia

To better understand the economic feasibility of biochar adoption in Cambodia, a conventional and unofficial market survey was conducted across both family-run enterprises and registered companies (in 2025). The goal was to assess retail pricing, feedstock types, packaging formats, and certification status. This survey revealed significant variation in product quality and pricing, reflecting the fragmented nature of Cambodia’s biochar supply chain. While some vendors offer certified rice-husk biochar with verified carbon content and pH levels, others sell ash-like products lacking formal testing or labeling. These inconsistencies contribute to farmer confusion and hinder widespread adoption. The following table summarizes key findings from the surveyed vendors.

Table 1-2 : The price of biochar in 2025: unofficial survey with sellers in Cambodia by 2025

Name of Seller	**Location**	**Packaging (kg)**	**Price per Bag**
Lala Garden	Battambang	25	$12.50
Husk Venture	Kampong Thom	25	$12.50
ATM Recycle	Phnom Penh	30	$12.00
We farm	Phnom Penh	15	$3.00
Angkor Farm	Siem Reap	10	$2.5
Takmao Farm	Phnom Penh	5	$2.5
Life Grow Tree	Siem Reap	3	$0.75
AGRONature	NA	10	$1.25

4. *Biochar research landscape in Cambodia*

Biochar adoption in Cambodia reflects challenges observed globally. An old study by Shackley et al. (2012) highlighted that small-scale biochar projects often encounter high costs, limited technical training, and weak institutional support. These barriers are evident locally, where advanced pyrolysis units remain rare, and most initiatives have been donor-driven pilots. Without integration into extension services or national policy, scaling has been limited.

One of the most comprehensive assessments remains the 2012 rice husk gasification study in Siem Reap. Field trials reported yield increases of up to 33% and carbon abatement potential of 0.42–0.86 t CO_2 per ton of husk, with an estimated economic value of $9–15 per ton. However, the study also flagged unresolved issues: replication across diverse soil types, health risks from crystalline ash, and wastewater management (Shackley et al. 2012). No subsequent large-scale trials were conducted, leaving these questions unanswered.

Further contributions by LORN et al. (2017) expanded the scope of Cambodian biochar research. Her 2017 tomato trials using rice husk and *Chromolaena odorata* biochar showed improvements in soil properties and plant growth, while later work on sandy soils confirmed biochar’s role in enhancing fertility and water retention. These studies provided valuable insights into feedstock diversity and soil responses, but they remained limited in scale and focused on non-rice systems. Importantly, although the data originated in 2018, her 2025 publication highlights the enduring relevance of these findings. This interval illustrates the rigorous peer-review process and the complexities of maintaining research continuity within the shifting landscape of regional development initiatives.

Pilot demonstrations, such as those presented by Chan Saruth at UN-CSAM, showcased kilns and TLUD stoves with positive crop responses. However, results remained anecdotal, lacking peer-reviewed publication and systematic dissemination.

Table 1-3 : Example of previous biochar research in Cambodia

Author, Year	Focus	Key Findings	Limitations / Gaps
(Chan 2020)	Biochar production technology (CVT kilns) and crop application (rice, vegetables, maize).	Developed local CVT and mobile kilns; Trials showed biochar + manure/NPK yielded significantly higher (e.g., +33% rice yield) than control.	Gaps in smallholder affordability emphasize that kiln designs must be adapted for local manufacturing to be cost-effective.
Shackley et al. (2012)	Sustainability of Gasification–Biochar Systems (GBS)	Proved RHC (Rice Husk Char) is a viable byproduct. 35% C content.	Focused on mill economics and carbon abatement; lacked soil application experiment
Lorn et al. (2025)	Nutrient-rich biochars (Siam weed & Durian shell)	Siam weed biochar (5 Mg ha^{-1}) is a "nutrient-rich" amendment. Reduced acidity and recycled K and P.	No leaching and irrigation included
LORN et al. (2017)	Effects of RHB vs. Chromolaena odorata (Siam weed) biochar on tomatoes.	Siam weed biochar significantly outperformed rice husk biochar in increasing tomato biomass and soil pH	Short-term pot study; no leaching included

5. Gap analysis

As summarized in Table 1-1, International research has explored biochar’s effects on soil properties, nutrient retention, water dynamics, and climate mitigation, often through controlled soil column experiments and field trials. However, Cambodian studies remain limited, focusing mainly on small-scale demonstrations and pilot projects with rice husk and other local feedstocks. The following table summarizes gaps from both global and Cambodian biochar research, highlighting the need for mechanistic, context-specific studies that this thesis aims to address.

Table 1-4 : Checklist for identifying research gaps in current research

Dimension	International	Cambodia	This research
Biochar + leaching	✓	✗	✓
Biochar + AWD*	✓	✗	✓
Biochar + leaching and AWD	✗	✗	✓
Biochar + yield	✓	✓	✓
Biochar + grain quality	✓	✗	✓
Biochar + soil properties	✓	✓	✗
Biochar + economic	✓	✓	✗

*At the time of gaps identifying, research on AWD and biochar in Cambodia has been limited. However, by 2025, evidence showed that it had been studied by Arun et al. 2025

Although research on biochar in Cambodia has expanded in recent years, a critical gap remains in understanding how nutrients move and are retained within the soil profile under typical rice-growing conditions. Most local studies emphasize crop yields or growth, approaches that often overlook the complex leaching of nitrogen and phosphorus during the alternating flooded and non-flooded cycles of rice cultivation. In addition, fertilization practices in Cambodia are poorly documented. Despite rapid growth in fertilizer imports and demonstration trials, most available information is outdated, with key references dating back more than a decade (see 1.6 above). Since then, the fertilizer market has continued to evolve, farmer access has expanded, and application behaviors have shifted in response to rising costs and climate variability. Yet, systematic data on how farmers currently use fertilizers, including application rates, timing, and integration with irrigation, remain scarce. This lack of up-to-date evidence creates uncertainty when designing agronomic experiments, as treatments may not reflect actual farmer practice.

To address this gap, a survey of rice farmers was conducted prior to the experiment, focusing on the types and amounts of chemical fertilizers applied in the field. The survey results provided a realistic baseline, ensuring that the experimental design was aligned with current practices rather than relying solely on historical reports.

This thesis addresses these mechanistic and contextual gaps by employing a soil column experimental design to track nutrient dynamics with greater precision. Specifically, it investigates how rice husk biochar interacts with chemical fertilizers to influence nutrient retention in the root zone. In addition, the study examines nutrient leaching and rice growth under two common irrigation regimes, Alternate Wetting and Drying (AWD) and Continuous Flooding (CF), to capture how water management interacts with biochar effects.

6. Outline and objectives

The overall objective of this dissertation is therefore to investigate the combined effect of biochar with chemical fertilizer to reduce nutrient leaching and enhance rice yield traits.

This dissertation is structured into the following five chapters.

- **Chapter I General Introduction:** In this chapter, the global description of the thesis is shown. The main contents were the important role of rice crop in Cambodia, the agricultural practice, the overview of fertilization and irrigation, the concept of leaching, and the use of biochar. The problems and knowledge gaps were also described in this part.
- **Chapter II Research Methodology**: is not a specific objective; however, this chapter gives additional information concerning the methodologies used, which are not always detailed in the published articles; yet they are important for the reproducibility of the experiment.
- **Chapter III:** This chapter provides an analysis of a soil column experiment designed to investigate the effects of biochar produced from rice husk on nutrient distribution in the soil, as well as its influence on rice growth and yield. The experiment was conducted under two conditions: disturbed and undisturbed soil, allowing for a comprehensive understanding of how biochar interacts with the soil environment.
- **Chapter IV:** This chapter provides an analysis of an experiment conducted to examine the combined effects of rice husk biochar and chemical fertilizers on rice yield, grain quality, and nutrient losses in Cambodian soils. The study was carried out under two irrigation regimes, Alternate Wetting and Drying (AWD) and Continuous Flooding (CF), to capture the biochar effect in each condition.
- **Chapter V:** General discussion and conclusions: At the end of the thesis, an overall discussion of the study is given, followed by insightful perspectives that could ameliorate future research.

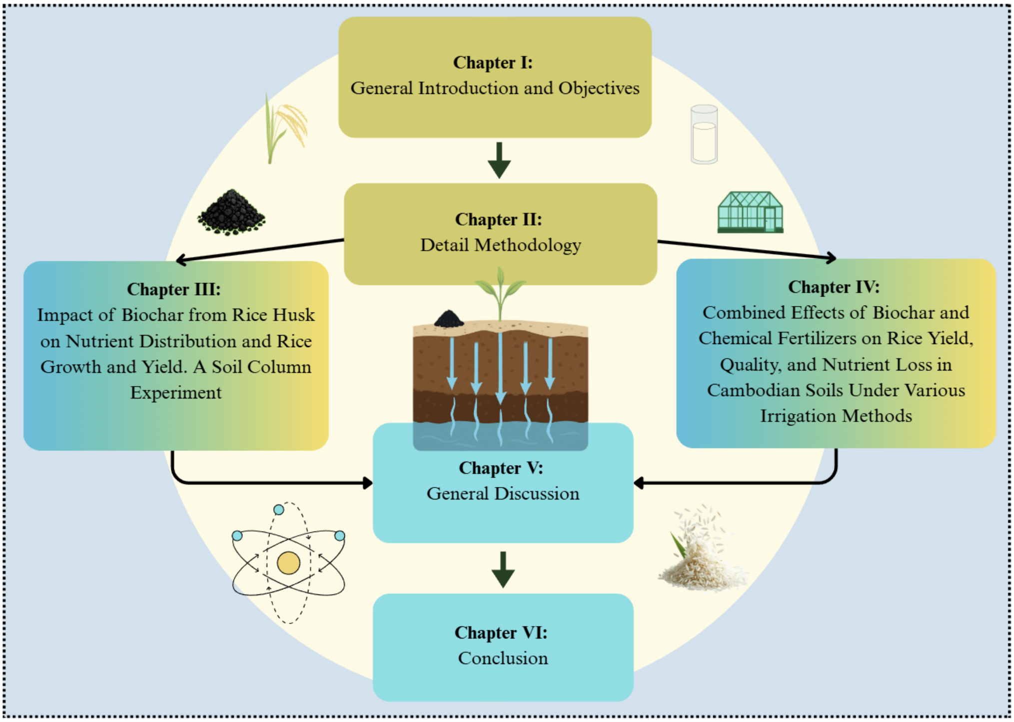


Figure 1-12: Thesis Composition Outline

Chapter 2

Research Methodology

1. General flow and approach

To achieve the desired objectives, two distinct experiments at separate structures, employing an identical methodological approach throughout both, were conducted. Each experiment was designed to explore specific variables while ensuring consistency in our techniques.

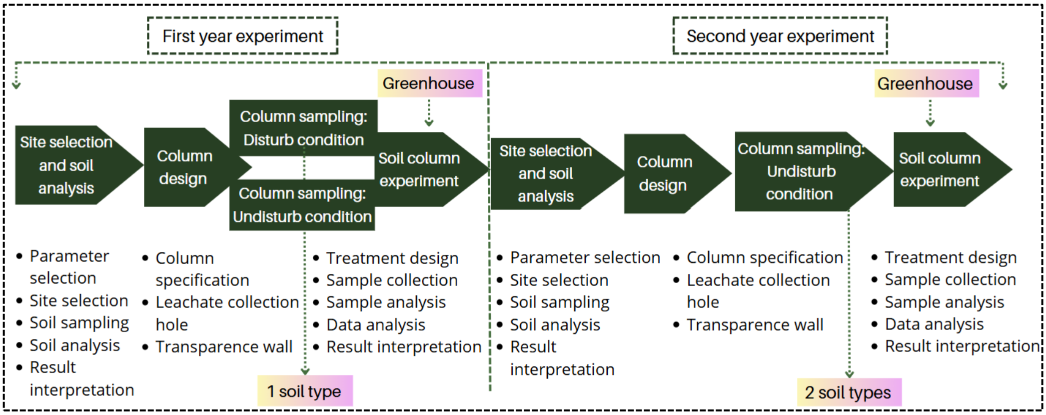


Figure 2-1: General flow of research methodology

2. Study area and experimental site

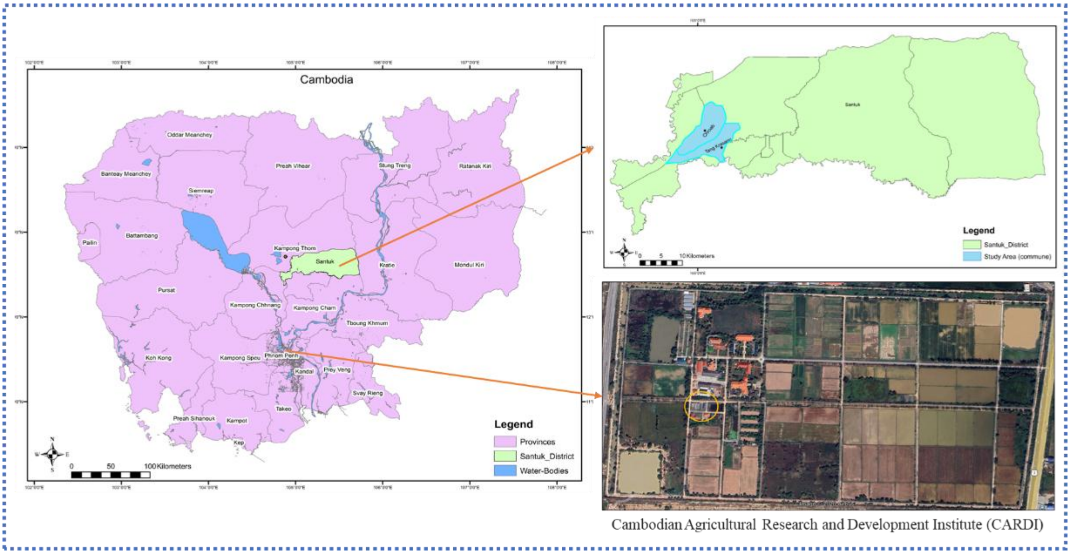
2.1. Experimental site

The experiment was conducted in a greenhouse at the Cambodian Agricultural Research and Development Institute (CARDI) in Phnom Penh in 2021 and 2022. The local altitude is 16m, with latitude 11°28’32.6"N and longitude 104°48’25.3"E. Köppen’s climate classification is Tropical Monsoon. The greenhouse comprises a glass panel roof and insect screens on the side walls. A black net was installed at 2.80 m above ground level to reduce net radiation. The greenhouse is oriented North-South, continually ventilated by an aperture at the top and the screen walls, constructed with metal tubes and a 10x5x4 m chapel style (Figure 2-2).

Figure 2-2: Greenhouse for column experiment

2.2. Study area

For this first-year experiment, soil was taken from the CARDI paddy field, while for the second-year experiment, soil was selected from two sites in Kampong Thom, located in the Santuk district (Figure 2-3). The research area was selected around the Taing Krasaing Irrigation Scheme (TKIS), located in the Kampong Thom province. TKIS was under upgrade, modernization, and rehabilitation through a key MOWRAM project. The farmers start to apply rice cultivation in the dry season, as most of the paddy fields are not usable in the rainy season.



Cambodian Agricultural Research and Development Institute (CARDI)

Figure 2-3: Map of study area and experimental site

3. Method for farmer survey

To inform fertilizer input planning for the second-year field trials, a cross-sectional survey was conducted among smallholder farmers. The survey aimed to capture demographic profiles, agronomic practices, input usage, and perceptions at a single point in time. Interviews were conducted face-to-face in Khmer to ensure cultural relevance and accurate comprehension.

3.1. Population and sampling

- Target population: Rice growers in Santuk district, Kampong Thom province of Cambodia.
- Sampling frame: Village lists provided by local agricultural offices.
- Sampling method: Stratified random sampling by villages that conduct both wet and dry season rice.
- Sample size: N = 150 farmers (computed via Cochran’s formula, 95% confidence, 5% margin of error).

3.2. Questionnaire structure

The instrument comprises three parts and 47 questions covering the farmer profile, crop production detail, and farmers’ engagement.

Table 2-1: Questionnaire structure

Part	Content	Question number
I	Farmer profile, household composition, landholding, and off-farm activities.	1-5
II	Crop production details, varieties, planting area, planting season, input doses (fertilizer, seed), pest/disease use and management, labour, yield, and post-harvest handling, income, and grain management.	6-38
III	Farmers' engagement, training attended, input procurement, credit/market access, and constraints.	39-47

Verbal informed consent was obtained from each farmer before the interview, with the study's purpose explained and assurances that participation was entirely voluntary and all responses would be kept anonymous. The detailed questionnaire is in Annex 2.

3.3. Summary of key findings

The surveyed farmers were predominantly smallholder rice producers with farming experience ranging from several years to multiple decades. Most households relied primarily on rice cultivation as their main source of income, while some also engaged in secondary off-farm activities to supplement household earnings. Farm sizes varied considerably among respondents, reflecting the diversity of smallholder production systems in Santuk district.

The survey revealed substantial variation in fertilizer management practices among farmers. Nitrogen fertilizer application rates reached up to 133 kg N ha^{-1}, while maximum phosphorus (P_2O_5) and potassium (K_2O) application rates were 46 and 30 kg ha^{-1}, respectively. Most farmers relied heavily on inorganic fertilizers, particularly urea and compound NPK fertilizers, with application decisions commonly based on personal experience and local practice rather than soil analysis or extension recommendations.

Rice residue management practices varied among surveyed farmers. Some farmers incorporated rice straw back into the soil after harvest, whereas others practiced open-field burning or removed residues from the field. Rice husk generated during milling was commonly used as boiler fuel or discarded as waste, depending on the scale of rice mill operations. These findings indicate the availability of rice biomass resources that could potentially be utilized for biochar production and soil amendment applications.

Table 2-2: Summary of key findings on nutrient management

Metric	Value
Total farmers surveyed	150
Number unaware of the nutrient leaching issue	143
Percentage unaware of the nutrient leaching issue	95%
Maximum Nitrogen use (kg N ha^{-1})	133
Maximum P_2O_5 use (kg ha^{-1})	46
Maximum K_2O use (kg ha^{-1})	30

The majority of farmers (95%) are unaware of nutrient leaching, which indicates that they do not recognize the potential for nutrients to wash away from the soil, ultimately hindering crop growth. This underscores the necessity of incorporating training and enhanced soil management techniques in the second-year experiment. The maximum input values for nitrogen (N), phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) will serve as benchmarks for local fertilizer practices. The survey findings were used to guide the design of the second-year field experiment. Fertilizer application rates observed among farmers were considered when selecting treatment levels to ensure that the experimental conditions reflected realistic local farming practices. Furthermore, the widespread use of inorganic fertilizers combined with limited awareness of nutrient retention and residue management supported the investigation of biochar as a potential strategy to improve nutrient use efficiency and enhance soil fertility under Cambodian rice cultivation systems.

Figure 2-4: Surveying with farmers in 2021

4. Soil characteristic analysis

Before starting the experiment, soil samples were collected from the paddy field to analyze key characteristics such as texture, nutrient content, organic matter, and water retention capacity. This initial analysis was crucial for understanding baseline conditions, enabling accurate comparisons throughout the study.

Soil pH was measured with the pH-H2O (1:5) soil/water suspension method. 25 g of air-dried 2 mm soil sample was placed in a clean beaker, then 125 mL of distilled water was added. The slurry sample was placed in the shaker (198 RPM for 30 minutes). Then, the soil sample was kept for 5 minutes, and was measured with a pH meter (Thermo Scientific™, 9617BNWP, USA).

Soil organic matter (SOM) was determined by the Walkley-Black method (Gupta 2014) following this procedure. 1 g of air-dried 2 mm soil sample was placed into a 250 mL Erlenmeyer flask, then 10 mL of 5% potassium dichromate ($K_2Cr_2O_7$) was added with a gentle swirl to wet the soil sample. After that, 20 mL of sulfuric acid (H_2SO_4) was added, swirled, and set for 30 minutes of insulation. Then, 50 mL of 0.4% of barium chloride ($BaCl_2$) was added to soil sample with a swirl to mix thoroughly. And the soil sample could stand overnight for precipitation. An aliquot solution was transferred into a colorimetric cuvette and the soil samples were measured using a spectrophotometer (Thermo Scientific™, GENESYS™ 10S, USA) at 600 nm absorbance.

The colorimetric determination of ammonium for total nitrogen (N) was performed using the digestion method (Baethgen & Alley, 1989; Bremner, 2016). A 1 g soil sample was placed in a digestion tube with 15 mL of H2SO4 and digested at varying temperatures: 100 °C for 10 minutes, 200 °C for 10 minutes, and 360 °C for 2 hours. After cooling, 50 mL of distilled water was added, mixed until sediment dissolved, and adjusted to a final volume of 100 mL. The mixture settled, and the clear solution was placed in vials for refrigeration. For analysis, 1 µL of sample was mixed with 5 mL of N1 reagent (Na salicylate and Na nitroprusside) and allowed to react for 15 minutes. Then, 5 mL of N2 reagent (Na hypochlorite) was added, and the solution was left for 1 hour for color development. The absorbance was measured at 655 nm using a spectrophotometer (Thermo Scientific™, GENESYS™ 10S, USA).

The OLSEN method (Olsen 1954; Zhou et al. 2001) was used to determine available phosphorus (P) by shaking the soil sample with 0.5M $NaHCO_3$ at pH 8.5 for 30 minutes at 25 °C. The sample was then filtered through Whatman 42 paper and mixed with 1.25M sulfuric acid, followed by the addition of 8 mL of distilled water. After remixing, 4 mL of reagent and 7 mL of distilled water were added to reach a final volume of 25 mL. Absorbance was measured at 882 nm using a Thermo Scientific™ GENESYS™ 10S spectrophotometer after 30 minutes.

5. Soil column design

In this study, soil columns were selected to assess nutrient leaching behavior, particularly in relation to rice growth and yield. Soil columns were constructed using thick-walled PVC pipes with a diameter of 15 cm and a length of 50 cm. Each pipe had a wall thickness of 5 mm, ensuring durability and structural integrity during experimentation. These PVC columns provided a stable framework for maintaining soil layering and bulk density, allowing precise observation of soil behavior under different conditions. The port position of the leachate collection is designed in various places and lengths based on each experiment.

5.1. Soil column sampling: disturbed condition

The disturbed soil column method involves reconstructing soil samples after they have been excavated, ensuring that the original layering and density are carefully simulated. In this experiment, soil samples were initially dug from rice fields and transported to the laboratory. To maintain accuracy, any plastics and stubble present in the soil were removed before the columns were prepared. The soil was then systematically repacked into the corresponding topsoil layer and plow sole, ensuring that the natural stratification was preserved. To achieve the field bulk density of each layer, the repacked soil columns were gently pressed using a wooden hammer, mimicking the natural compaction processes found in the field.

5.2. Soil column sampling: undisturbed condition

The undisturbed soil column method is designed to preserve the natural structure and composition of the soil, ensuring that its physical and chemical properties remain unchanged. To achieve this, the soil column is carefully extracted from the field using specialized coring tools, preventing any disruption to its natural layers. Maintaining the original state of the soil is critical for experiments that focus on water movement, root penetration, and soil compaction. The sample is transported and preserved in rigid containers to avoid structural shifts. These undisturbed columns provide valuable insights into the natural behavior of soil in its original environment, making them ideal for studying hydrological properties and nutrient distribution without artificial influences.

Figure 2-5: Soil column sampling: undisturbed condition

5.3. Soil column preparation for experiment

After soil column design and sampling, the base of each column was connected to a faucet system to facilitate leachate collection. The soil columns were installed on sturdy metal shelves inside a greenhouse, ensuring stability and uniformity. Each column was fitted with transparent tubing and valves to regulate water input and direct leachate into collection containers placed beneath. Once stabilized, controlled irrigation regimes were applied, including alternate wetting and drying (AWD) and continuous flooding (CF), with water volumes carefully measured and recorded. Fertilizer inputs were added according to the experimental design, and leachate samples were collected at regular intervals. These samples were stored in airtight bottles and refrigerated until chemical analysis. The greenhouse environment provided consistent conditions for monitoring plant growth, water dynamics, and nutrient leaching, while the column setup allowed precise control over treatments and reliable data collection.

Figure 2-6: Soil column sampling: undisturbed condition

6. Sample analysis

6.1. *Leachate analysis*

Leachate samples were analyzed for ammonium (NH_4^+), nitrate (NO_3^-), and ortho-phosphate (PO_4^{3-}) using a Lovibond photometer. For NH_4^+, 0.1 mL of leachate was added to capped vials, followed by one pack of Vario F5 Powder. The vials were shaken until dissolved and reacted for 20 minutes. After zeroing the blank (deionized water), samples were measured, and results were displayed as mg L^{-1} of NH_3^-. To convert to NH_4^+, multiply by 1.29.

NO_3^- was analyzed using the testing tube method. A 1 mL leachate sample was added to white-capped vials along with one pack of Vario Powder (Nitrate Chronotropic). The vials were capped and inverted to mix, then allowed to react for 5 minutes. Deionized water was used as a blank in the sample chamber to zero the device. Each leachate sample was then tested, with results displayed in mg L^{-1} of NO_3^-

PO_4^{3-} was analyzed using the ortho method with a tablet by filling clean 24 mm Ø vials with 10 mL of the leachate sample and sealing them. After zeroing the device, P1 (PHOSPHATE-1) and P2 (PHOSPHATE-2) tablets were added to the sample and crushed with a clean stirring rod. The vials were sealed tightly and swirled until the tablets dissolved. They were then placed back in the sample chamber, and after a 10-

minute reaction period, the measurement started automatically, displaying results in mg L^{-1} of PO_4^{3-}.

Figure 2-7: Rice growth monitoring activity

6.2. *Plant analysis*

6.2.1. NO_3^- content in leave, stem, and root

The salicylic acid method was used to evaluate the nitrate content in the rice plant (Zhao and Wang 2017). The method is free of interferences, reliable, and stable; thus, it can be a good choice for the measurement of nitrate in plant tissues. Nitrosalicylic acid is formed by the reaction of nitrate and salicylic acid under highly acidic conditions. The complex is yellow under basic (pH > 12) conditions with maximal absorption at 410 nm. The absorbance is directly proportional to nitrate content. Therefore, tissue nitrate content can be calculated based on their absorbances. This method is suitable for the determination of nitrate concentration in plants.

Procedure:

0.1 g sample of young leave, old leave, stem, and roots were ground into the powder with the frequency of 30/sec for 5 min using a RETCH MM400 and it was transferred into the tube. 1 ml deionized water was added into the tubes and boil at 100 °C for at least 20 min. The sample was centrifuged at 15,871 x g for 10 min, and then 0.1 ml of the clear phase, called “supernatant,” was transferred into a new 12mL tube while 0.1 ml of deionized water was used as a control. After that, 0.4 ml of salicylic acid-sulphuric acid was added to each tube, mixed well, and incubated the reactions for 20 min at room temperature. After incubation, 9.5 ml of 8% (w/v) sodium hydroxide (NaOH) was added into each tube and cooled down the tubes to room temperature (about 20-30 min). The sample was transferred into 96-well plate and measured at 820-nm wavelength using a microplate reader with the control as the reference. The result of nitrate concentration was calculate based on the standard curved regression equation.

To make the standard curve, 1 ml, 2 ml, 3 ml, 4 ml, 6 ml, 8 ml, 10 ml, and 12 ml of NO_3^- standard solution (500 mg/L) was transferred to eight 50 ml flasks respectively, and deionized water was added to each solution to reach the total volume of 50 ml. The concentration of the series of standard solution was 10, 20, 30, 40, 60, 80, 100, and 120 mg/L, respectively. And the molarity of 10, 20, 30, 40, 60, 80, 100, and 120 mg/L KNO_3 is 0.0007, 0.0014, 0.0021, 0.0029, 0.0043, 0.0057, 0.0071, 0.0086 mol/L, respectively. After that, 0.1 ml of each standard solution was transferred into a 12-ml tube while 0.1 ml of deionized water was used as a control. Then, 0.4 ml of salicylic acid-sulphuric acid was added into each tube, mixed well, and then incubated all reactions at room temperature for 20 min. Then, 9.5 ml of 8% (w/v) NaOH was added into each tube, cooled down the tubes (heat was generated due to the reaction) to room temperature (about 20-30 min), and the standard solution was transferred into 96-well plate and measured at 820-nm wavelength using a microplate reader. The nitrate content was calculate using the following equation:

$$Y = \frac{\mathrm{CV}}{W}$$

Were, Y is nitrate content (µg/g), C is nitrate concentration calculated with the standard curve regression equation (µg/mL), V is the total volume of extracted sample (ml) and W is weight of sample (g).

6.2.2. NH_4^+ content in leave, stem, and root

Ammonia reacts with hypochlorite and forms a monochloramine, which reacts with phenol to an indophenol derivative that has deep blue color and displays maximal absorbance at 620 nm. In this method, a high-throughput analysis was used as a protocol for 96-well plate format that allows the colorimetric quantification of glyoxylate and ammonia from a single plant extract (Bräutigam et al. 2007). Extract purification with chloroform and activated charcoal efficiently removed interfering compounds, thereby making the procedure appropriate for plant extracts.

Procedure:

100 mg of sample was ground into powder and extracted in 1 mL of 100 mM perchloric acid (HCl) and subsequently 500 µL of chloroform. The sample was rotated at 4°C for 15 min, then centrifuged at 12000g for 10 min. The aqueous phase was transferred to the tube containing 50mg of acid-washed activated charcoal and centrifuged at 8°C, 20000g, for 5 min. The clear phase called "supernatant" obtained after charcoal treatment was diluted 1:1 (v/v) in 100 mL of HCl. Then, 20 uL of this solution was mixed with 100 uL of a 1% (w/v) phenol–0.005 % (w/v) sodium nitroprusside (S.N.P) in water, and 100 uL of a 1% (v/v) sodium hypochlorite-0.5% (w/v) sodium hydroxide solution in water. This mixed sample was incubated at 37°C for 30 min, transferred into a 96-well plate, and light absorption at 620 nm was measured using a microplate reader.

6.2.3. PO_4^{3-} content in leave, stem, and root

Here, we present a simple, high-throughput colorimetric microplate technique to measure Pi contents in rice (Oryza sativa) leaf tissues, based on the molybdenum blue reaction (Wissuwa et al. 2020).

Procedure:

A 50 mg sample of young leave, old leave, stem, and roots were ground into the powder and extracted by 200µL of 5.5% (w/v) perchloric acid (HCl). The sample was incubated on ice for 3 hours and then the clear phase called "supernatant" was transferred to a 96-well plate. After that, the supernatant was diluted with 5.5% (w/v) HCl by adding up to 80µL of the final volume. Then, molybdate blue reagent (containing of ammonium molybdate 0.4% (w/v) in 0.5 M H_2SO_4 (solution A) with 10% ascorbic acid (solution B) (A: B = 6: 1)) was added to the supernatant (supernatant: molybdate blue reagent = 1:2) and incubated at 40°C for 20 min. The supernatant was measured at 820-nm wavelength using a microplate reader.

The PO_4^{3-} content was analyzed by comparing the absorbance with the standard curve, and the PO_4^{3-} concentration was calculated in micromoles per gram fresh weight (µmol/g). The PO_4^{3-} concentrations used to generate a standard curve should be in the range of 0.1–40 µg/mL (equivalent to 0.74–294.12 µM). To generate standard curve, KH_2PO_4 was used to prepared a serial dilution of known concentration in the range of 0.1-40 µg/mL (equivalent to 0.74–294.12 µM). Then, 160 µL of molybdate blue reagent was added to 80 µL of this phosphate standard. The mixed solution was then incubated at 40°C for 20 min, transferred into 96-well plate and measured at 820-nm wavelength using a microplate reader.

6.3. Grain analysis

6.3.1. Grain yield measurement

Rice samples were measured for plant biomass, tiller number, grains per panicle, grain weight per panicle, panicle length, root biomass, root length, and total yield. The plant height and chlorophyll SPAD of each soil column were measured at 7-day intervals using a 3-m measuring tape and SPAD device. At the maturity period, plant samples were split into straw and panicle to count the tiller number. The samples of panicles out of the total were selected randomly to count the grains per panicle. The soil column was carefully broken to keep the root structure. The root area was shaped and soaked in water to be cleaned. Then, the root length was measured. The dried weight of straw, leaves, and roots was determined after oven-drying at 70 ◦C to a constant weight for 48 hours.

6.3.2. Protein content in rice grain

Protein is an essential component required for growth, antibody production, and immunity in human beings. Total protein was estimated by modified Lowry 's method given by Hartree, 1972. Determination of protein concentration by ultraviolet absorption depends on the presence of aromatic amino acids in the proteins. Powdered samples were subjected to the extraction of protein by 0.1M phosphate buffer with a pH of 7.4. One gram of sample from each entry was macerated with 50 ml of phosphate buffer using a Pestle and Mortar and centrifuged at 4000 rpm for 20 minutes. The supernatants were collected for protein estimation by discarding the pellet. The above steps were performed for each entry separately until a clear extract was obtained. The extract was stored in a deep freezer until further analysis.

Extracted samples of 0.2 mL were taken into a test tube, and the volume was made up to 1 mL with distilled water. To it, 4.5 ml of alkaline CuSO4 reagent was added and incubated at room temperature for 10 minutes, followed by 0.5 ml of Folin 's phenol reagent. The contents were mixed well, and the absorbance was measured at 650 nm after 15 minutes in a spectrophotometer. From the standard graph, the amount of protein in the given unknown solution was calculated.

6.3.3. Amylose content in rice grain

Amylose content of milled rice is determined by using the colorimetric iodine assay index method. 100 mg of ground rice was added to a 100 ml volumetric flask, along with 1 ml of 95% ethanol and 9 ml of 1M sodium hydroxide. The mixture was heated in a boiling water bath to gelatinize the starch, then cooled for 1 hour. Distilled water was added, and the solution was mixed. From this, 5 ml was transferred to a new flask, and 1 ml of 1M acetic acid and 2 ml of iodine solution were added, with the volume adjusted to 100 ml with distilled water. The sample stood for 20 minutes before measuring absorbance at 620 nm to determine amylose content on a dry weight basis. For the standard curve, 40 mg of potato amylase was treated similarly with ethanol and sodium hydroxide, then heated and cooled. Various volumes were acidified and treated as above, with absorbance values measured at 620 nm against amylose concentration to establish a conversion factor.

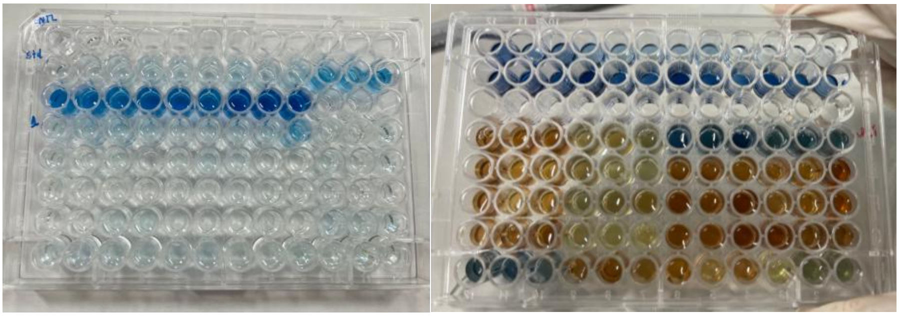


Figure 2-8: Preparation of plant and grain solutions for analysis.

Chapter 3

Impact of Biochar from Rice Husk on Nutrient Distribution and Rice Growth and Yield. A Soil Column Experiment

The content of this chapter has been published in the **Journal of Soil Science and Plant Nutrition**: Chenda Lai, Ratha Muon, Veasna Touch, Sarith Hin, Pascal Podwojewski, Pinnara Ket, Pascal Jouquet, Aurore Degré, and Vannak Ann. *Impact of Biochar from Rice Husk on Nutrient Distribution and Rice Growth and Yield: A Soil Column Experiment*, **Journal of Soil Science and Plant Nutrition**, Volume 24, pages 159–171 (2024). https://link.springer.com/article/10.1007/s42729-023-01539-2

Prelude explaining the importance of this chapter in relation to the study's objectives:

This study uses soil column experiments to examine nutrient leaching dynamics in rice fields, highlighting the importance of soil fertility for crop productivity. While prior research has looked at various soil amendments, the combined effects of chemical fertilizers and biochar on nutrient retention remain underexplored. Addressing the lack of standardized methods for analyzing nutrient leaching in tropical soils, this research employs experimental setups to study the movement of ammonium, nitrate, and phosphate through different soil layers. By simulating field conditions with soil columns, the study aims for precision and reproducibility in assessing nutrient distribution. The findings bridge engineering and agronomy, focusing on improving methodologies for nutrient leaching assessment to promote sustainable agricultural practices and better soil fertility management.

Abstract

Cambodia planned for developing its rice sector into a major rice-exporting country. A key concern is that soil fertilization makes an issue of its rice production, and that nutrients leaching into the environment lead to lower rice nutrient uptake and yield. Not only known as a potential enhancement of soil fertility, but carbonized waste biochar is also a relevant nutrient leaching reduction and is introduced in many regions. Here to assess a mixture of the chemical fertilizers and rice husk biochar affecting nutrients leaching into the topsoil layer and plow sole of soil columns, and to evaluate their combined effects on rice growth and yield. In leachate from these two soil layers except ortho-phosphate (PO_4^{3-}) content, CHEM + BIO4 (chemical fertilizers + biochar 4t ha^{-1}) treatment applied together significantly reduced ammonium (NH_4^+) and nitrate (NO_3^-) contents more than CHEM did alone, especially from the plow sole, suggesting their combination, and biochar sorption capacity, are beneficial to nitrogen use by plants. CHEM + BIO4 enhanced rice yield, plant biomass, tiller number, panicle length, grains per panicle, and grain weight per panicle. These findings indicate biochar amendments can minimize N leaching, but not P leaching, thus promoting their use for rice production.

Keywords: Soil compaction; Mixed rice husk biochar; Nutrient loss by leaching; Irrigated rice; Rice productivity

1. Introduction

Rice is a major crop in Cambodia, and it plays a significant role in the country's economy and food security (Kea et al. 2016; Mishra et al. 2018). Most of the rice production in Cambodia is carried out through traditional farming methods, with smallholder farmers cultivating rice on small plots of land (i.e., rice fields) using simple tools and techniques (Cramb et al. 2020). It should be noted that some rice fields are situated under reconstituted and/or conserved conditions, especially after crop rotation and/or deforestation (Hok et al. 2015; Kong et al. 2021). Under the two conditions, this conventional tillage in those rice fields has created their surface layer of soil (called topsoil layer) and compacted layer of soil (plow sole), usually seen in tropical agriculture (Wasaya et al. 2019). Plowing the soil helps to prepare the topsoil surface for new plantation by burying the straws and the potential weeds (Azimi-Nejadian et al. 2022; Jin et al. 2020) and allows water percolation and nutrients to reach the rooting zones (Islam et al. 2021), especially to release an unavailable form of nitrogen (N) (e.g., dinitrogen (N_2), ammonia (NH_3^-), hydroxyammonia (NH_2OH)) (Singh et al. 2020). The release of the N content available for rice growth occurs after an N fixation and nitrification process (Hirsch and Mauchline 2015; Zhang et al. 2021). Moreover, during the implementation of turning soil, the separation between the soil particles and the diameter of capillary tubes increased, thus enhancing soil moisture in the topsoil layer (Rehm et al. 2021). In contrast to the latter, the plow sole can limit water percolation beyond the rooting zones and keeps the rice fields under water depth during the rice growth (McDonald et al. 2006) and can limit the nutrient leaching (Patel and Singh 1981). Even though this conventional tillage is relevant to rice production, and this since antiquity (Nesbitt and International Rice Research Institute 1998). In recent years, there has been a growing trend towards mechanization and the adoption of modern farming practices in rice cultivation, such as the use of agrochemicals (Chhay et al. 2017; Kimkong et al. 2023).

In this sense, to increase their rice yield, Cambodian farmers have often relied on some kinds of convenient and quick-acting chemical fertilizers, especially N (i.e., urea fertilizer amendment) (Dong et al. 2015). More than 55% of the N fertilizer applied to irrigated land (in tropical agriculture) was not taken up by rice itself (Inamura et al. 2009; Zhu et al. 2016). This wasted N is thought to be lost from the rice fields mainly through surface runoff, NH_3^- volatilization, and especially its leaching (Dong et al. 2015; Li et al. 2017). Regarding the N leaching in Cambodia, from the rice fields into the environment, there is still a limited awareness of it ((Verma et al. 2020); survey data, pers. communication). In addition to the N leaching, long-term use of phosphorus (P) fertilizer or manure can also increase the potential for P leaching into groundwater and surface water (Kang et al. 2011). P leaching is, on the other hand, the concerned case because the excess P fertilizer is negatively impacting water quality (Nelson et al. 2005) leads to the eutrophication phenomena (Huang et al. 2018). In previous studies, controlled-release fertilizers (e.g., polymer-coated fertilizer, granular fertilizer, and zeolite) have been used to reduce nutrient leaching (N and P) from the rice fields as seen in other tropical areas (Chen et al. 2018). However, the concern of these controlled-release fertilizers is the need for high-cost materials, which are a significant obstacle restraining their widespread application in agricultural production (Lawrencia et al. 2021; Vejan et al. 2021). Hence, it is important to find efficient and comprehensive strategies (e.g., use of other feedstocks (Liu et al. 2016b; Ma et al. 2019; Munda et al. 2018; Soinne et al. 2014; Xu et al. 2014; Yin et al. 2021)). Those feedstocks include wood biochar, rice straw biochar, converted agricultural residues, bamboo biochar, corn stover, oak wood, spruce, and/or scots pine to control N and P leaching in the rice fields. Interestingly, Sun et al. (2018a) experimented with the application of wood biochar which influences NH_3^- volatilization and N leaching (i.e., ammonium (NH_4^+), nitrate (NO_3^-), and N in oxidizing state (ON)) in the rice fields. Their results showed that one-time biochar application reduced NH_4^+, NO_3^-, and ON leaching by 7.3-11.8%, 6.3-25.0%, and 31.1-41.7%; respectively, and thereby significantly reduced total nitrogen (Total N) leaching by 23.1-32.4% compared to the experiment without biochar. In another study, wood biochar at a higher rate of 10% w/w (i.e., biochar weight /soil weight) decreased the ortho-phosphate (PO_4^{3-}) leaching by 37.7% (Rubin et al. 2020). A study by Chen et al. (2021) showed that the application of rice straw biochar at a rate of 20t ha^{-1} reduced the NO_3^- and Total N leaching by 30.0%-38.6% and 12.8%-13.4%, respectively. However, more than 30t ha^{-1} of the rice straw biochar had negative effects on wheat yield, and nutrient uptake (Sun et al. 2019).

Besides the two above-mentioned materials, a rice husk biochar has also shown a significant reduction of nutrient leaching and is being used in many Asian countries (Asai et al. 2009; Mohammadi et al. 2017; Sarong and Orge 2015; Singh et al. 2018; Wantaneeyakul et al. 2021; Yoo et al. 2014). With its high surface area and ion exchange capacity (e.g., anion or cation depending on burning temperature and feedstocks used (Brassard et al. 2019a; Lawrinenko and A. Laird 2015; Rizwan et al. 2016)), the rice husk biochar can minimize the nutrient leaching through different soil layers during the rice growth, thus enhancing its yield (Brassard et al. 2019b). In recent years, unaffordable prices of chemical fertilizers have prevented farmers from applying them enough. As reported, about 80% of farmers underused chemical fertilizers, with financial consideration as the main reason, while others overused them to increase their profit (Chhay et al. 2017; Ye et al. 2022). Consequently, as mentioned in previous studies, their overuse leads to nutrients leaching into the environment (Huang et al. 2017b; Ke et al. 2018; Tyagi et al. 2014), thus causing public health issues (Ahmed et al. 2017; Dimkpa et al. 2020; Erisman et al. 2013; Gwenzi et al. 2015). In Cambodia, many studies highlighted that one of the main causes of water quality degradation was the use of chemical fertilizers (Chhun et al. 2020; Ebers et al. 2017). This use threatens Cambodian people in the countryside, who still use groundwater and surface water in their daily life (Bun et al. 2021; Guppy and Shantz 2011) as their living areas are around the rice fields. Therefore, in this study, the rice husk biochar was introduced because it has a potential of carbonized organic waste from agriculture (Das et al. 2023) and is easily produced by commercial or local farmers in Cambodia. The study's objectives were to 1) assess the effects of chemical fertilizers combined with rice husk biochar on the NH_4^+, NO_3^-, and PO_4^{3-} contents leaching into the topsoil layer and plow sole using a soil column experiment, and 2) evaluate how the occurrence of biochar and its quantity is affecting the rice growth and yield. Use of the biochar will have a positive impact on the nutrient leaching, and the rice growth and yield. However, when the biochar is too high, a negative impact could be expected.

2. Material and methods

2.1. Column experimental design

The experiment was carried out in a greenhouse of the Cambodian Agricultural Research and Development Institute (CARDI, latitude 11°28'32.33" N and longitude 104°48'25.37" E in a tropical climate) starting from June to the end of September 2021. A soil "Prateah Lang (sand over clay, (White et al. 2006))" was selected for this experiment as it is the most abundant soil group (28%) among the 11 soil groups of Cambodia's irrigated land for rice only (White et al. 1997). Specifically, the FAO/UNESCO soil classification system would classify this soil "Prateah Lang" mainly as Gleyic Acrisols (Ballester et al. 2021b). Two sets of soil column samples represent the reconstituted and conserved conditions of the rice fields in tropical agriculture (**Error! Reference source not found.** A). Under each condition, all the soil (column) samples were selected at three different sampling profiles (i.e., until horizon B defined by the FAO Guidelines for Soil Description (FAO 2006)). And each soil column represents two soil layers (i.e., topsoil layer and plow sole; Figure 3-1. B). For the reconstituted conditions, the soil samples were dug from the rice fields. In the laboratory, after removing plastics and stubbles, the soil columns were prepared and repacked into the corresponding topsoil layer and plow sole. And subsequently, the soil columns were gently pressed by a wooden hammer to reach the field bulk density of each layer (see, **Error! Reference source not found.**). For the conserved conditions, the soil columns were directly sampled from the rice fields to avoid any disturbance of the topsoil layer and plow sole, using a designed Thick-Wall 5 mm PVC pipe (50 cm long, and 15 cm in diameter), to keep the original structure of each layer.

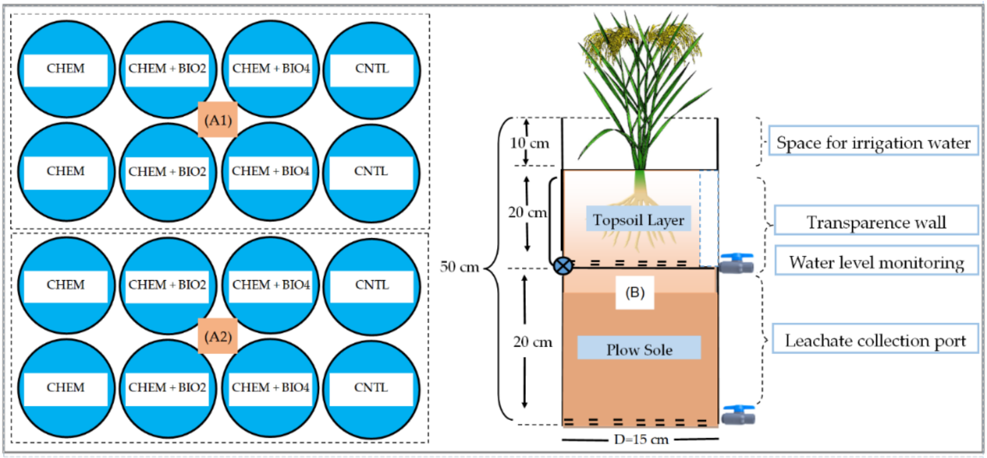


Figure 3-1: Two sets of the soil column samples were designed for the rice fields' representation. Two sets of the soil column samples were designed for the rice fields' representation using a soil group (called Prateah Lang (Gleyic Acrisols)) under reconstituted (A1) and conserved (A2) conditions. A soil column (B) represents the topsoil layer and plow sole. CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + Biochar 2t ha^{-1}; CHEM + BIO4, CHEM + Biochar 4t ha^{-1}; CNTL, Control (no chemical and no biochar)

A rice husk biochar (hereafter, biochar) was burned in a muffle furnace at 400 °C for 4 hours (Singh Karam et al. 2022b). Before rice sowing, the biochar was added to each soil column, about 10-15 cm in the topsoil layer, as an amendment during the soil preparation. Different treatments were applied in each soil column: chemical fertilizers (CHEM) (including urea, DAP, and KCl) at a ratio rate of 60:30:30 of NPK, respectively, CHEM + BIO2 (i.e., CHEM + Biochar 2t ha^{-1}), CHEM + BIO4 (CHEM + Biochar 4t ha^{-1}), and CNTL, control (i.e., no chemical and no biochar). A rice cultivar (locally named Sen Pidao) was selected for the direct seeding irrigation method (Figure 3-1. B). During the whole experiment, following the soil group considered, the CHEM treatment was applied two times in each soil column: the first time (NPK: 60 kg ha^{-1}, 50 kg ha^{-1}, 50 kg ha^{-1}; respectively) during the soil preparation at the beginning, and the second time (only N: 100 kg ha^{-1}) during the boosting stage (i.e., 40 days), except for the CNTL treatment. To collect the leachate, the designed Thick-Wall 5 mm PVC pipe was drilled with two holes from the two soil layers: one hole at a depth of 30 cm (from the top) for the topsoil layer, and another one at 50 cm for the plow sole. The two holes were wrapped in a nylon mesh to prevent an interruption of the sedimentation and were equipped with a faucet.

2.2. Measuring biochar and soil characteristics

Triplicate samples of the biochar were analyzed for its basic characteristics, including pH (1:5 H_2O), total nitrogen (Total N) (%), available phosphorus (P) (mg L^{-1}), and exchangeable potassium (K) (cmol kg^{-1}) following the methods described for the soil analysis (below), except for available N (g 100 g^{-1}). The latter was measured with NH_4N-KCl extraction and Kjeldahl methods (Keeney and Nelson 1983; Sáez-Plaza et al. 2013).

Triplicate soil samples from each layer of the three sampling profiles were measured. The soil characteristics (such as bulk density (BD) (g cm^{-3}), pH, soil organic matter (SOM) (%), Total N (%), available N (g 100 g^{-1}), ammonium (NH_4^+) (mg 100 g^{-1}), available phosphorus (P) (mg L^{-1}), and exchangeable potassium (K) (cmol kg^{-1})) were measured immediately after soil sampling. BD was measured using volumetric metal rings (5 cm long, 5 cm in diameter). Soil pH was measured with the pH (1:5 H_2O) soil/water suspension method (Rayment and Higginson 1992). Soil organic matter (SOM) was measured with the Walkley-Black method (Gupta 2014). Total N and NH_4^+ contents were measured with Kjeldahl method (Baethgen and Alley 1989; Bremner 2016; Gupta 2014), whereas available phosphorus (P) was measured with Olsen method (Olsen 1954; Zhou et al. 2001). Exchangeable potassium (K) was measured with the Flame photometer method (Gupta 2014).

Table 3-1: Mean values (± 1 SD, standard deviation) for the rice husk biochar (n = 3) were randomly estimated from a 3-kg rice husk biochar, and the topsoil layer (n = 9) and plow sole (n = 9) of the rice fields were estimated from the three soil profiles. SOM stands for soil organic matter; Total N for total nitrogen; Available N for available nitrogen; Exchangeable K for exchangeable potassium; and NH_4^+ for ammonium. The numbers (in bold) were significantly different between the two soil layers (T-test, $p < 0.05$)

Description	**Bulk density (BD) ($g\ cm^{-3}$)**	**pH (1:5 H2O)**	**SOM (%)**	**Total N (%)**	**Available N ($mg\ 100g^{-1}$)**	**Available P ($mg\ 100g^{-1}$)**	**Exchangeable K ($cmol\ kg^{-1}$)**	**NH_4^+ ($mg\ 100g^{-1}$)**
Rice husk biochar	-	7.80 ± 0.162	-	5.60 ± 0.030	29.60 ± 0.009	2.60 ± 0.02	4.03 ± 0.042	-
Topsoil layer (0-20 cm)	1.60 ± 0.052	6.10 ± 0.144	**0.45** ± 0.091	**0.03** ± 0.005	-	**5.97** ± 0.213	**0.17** ± 0.008	5.91 ± 0.172
Plow sole (20-40 cm)	**1.93** ± 0.02	6.52 ± 0.432	0.13 ± 0.009	0.02 ± 0.002	-	4.50 ± 0.327	0.13 ± 0.017	5.94 ± 1.105

The basic characteristics of biochar and soil as measured from the topsoil layer and plow sole are shown in Table 3-1. Total N and exchangeable K values for biochar with alkaline pH were high, while available P was low. Soil organic matter (SOM), Total N, and exchangeable K values for the topsoil layer were significantly higher than those for the plow sole: t (10) = - 7.84, $p < 0.001$; t (10) = - 4.24, p = 0.001; t (10) = -3.96, p = 0.002, respectively. The bulk density (BD) of the plow sole was significantly higher than that of the topsoil layer: t (10) = 13.70, $p < 0.001$. However, neither soil pH nor NH_4^+ values for the two soil layers were significantly different: t (10) = -2.12, p = 0.059; t (10) = -0.17, p = 0.865, respectively.

2.3. *Measuring soil column leachate*

Triplicate leachate samples from each faucet of the topsoil layer and plow sole were collected at 7-day intervals using the sampling bottle container (polypropylene material). The leachate samples were measured immediately for ammonium (NH_4^+) (mg L^{-1}) and nitrate (NO_3^-) (mg L^{-1}) with Vario Tube Test, and ortho-phosphate (PO_4^{3-}) (mg L^{-1}) with the ortho method with table. All the three variables were measured using a photometer (Part Number 214020, MD600, Lovibond, Germany).

2.4. *Measuring rice growth and yield*

Triplicate rice samples were measured for plant biomass (g plant-1), tiller number, grains per panicle, grain weight per panicle (g), panicle length (cm), root biomass (g), and root length (cm), except for total yield (g plant^{-1}). The plant height of each soil column was measured at 7-day intervals using a 3-m measuring tape. At the maturity period, plant samples were split into straw and panicle to count the tiller number. The samples of panicle out of the total were selected randomly to count the grains per panicle. The soil column was carefully broken to keep the root structure. The root area was shaped and was soaked in water to be cleaned. Then, the root length was measured. The dried weight of straw, leave, and root was determined after the oven-drying at 70 ˚C to a constant weight for 48 hours.

3. Data analysis

All statistical analyses were performed in R (R Core Team 2021). A one-way analysis of variance (One-way ANOVA) was performed to assess the effects of chemical fertilizers, and their combination with biochar on nutrient leaching, and the differences among treatments which enhanced all the variables describing rice growth and yield. All effects and differences were statistically significant, followed by post-hoc comparisons, using the Tukey's HSD (Honestly Significant Difference) test differed at the $p < 0.05$ level. The significant differences in variables of the biochar and the two soil layers were computed by the T-test for Equality of Means differed at the $p < 0.05$ level. All data were log-transformed [$y = \log(x+1)$] to improve the normality and homogeneity of variance. The graphics of nutrient leaching (or leachate) accumulation, rice growth and yield were plotted using Origin(Pro).

4. Results

4.1. *Nutrient leaching in the topsoil layer and plow sole*

There was no significant difference in the nutrient leaching between the reconstituted and conserved conditions (Lai et al. 2022). However, a rising nutrient leaching (NH_4^+, NO_3^- and PO_4^{3-}) during the experiment (7-56 days) confirmed higher leachate measured in the topsoil layer than that in the plow sole (Figure 3-2). Comparing the CHEM treatment with other treatments including biochar (i.e., CHEM + BIO2 and CHEM + BIO4), the biochar significantly affected the NH_4^+ and NO_3^- contents leaching into the topsoil layer ($p < 0.05$), but not the PO_4^{3-} content (Figure 3-3). However, into the plow sole, the biochar did not significantly affect the NH_4^+ content but reduced the NO_3^- content ($p < 0.05$). In any case, the CNTL treatment highlighted significantly the lowest values for these three variables.

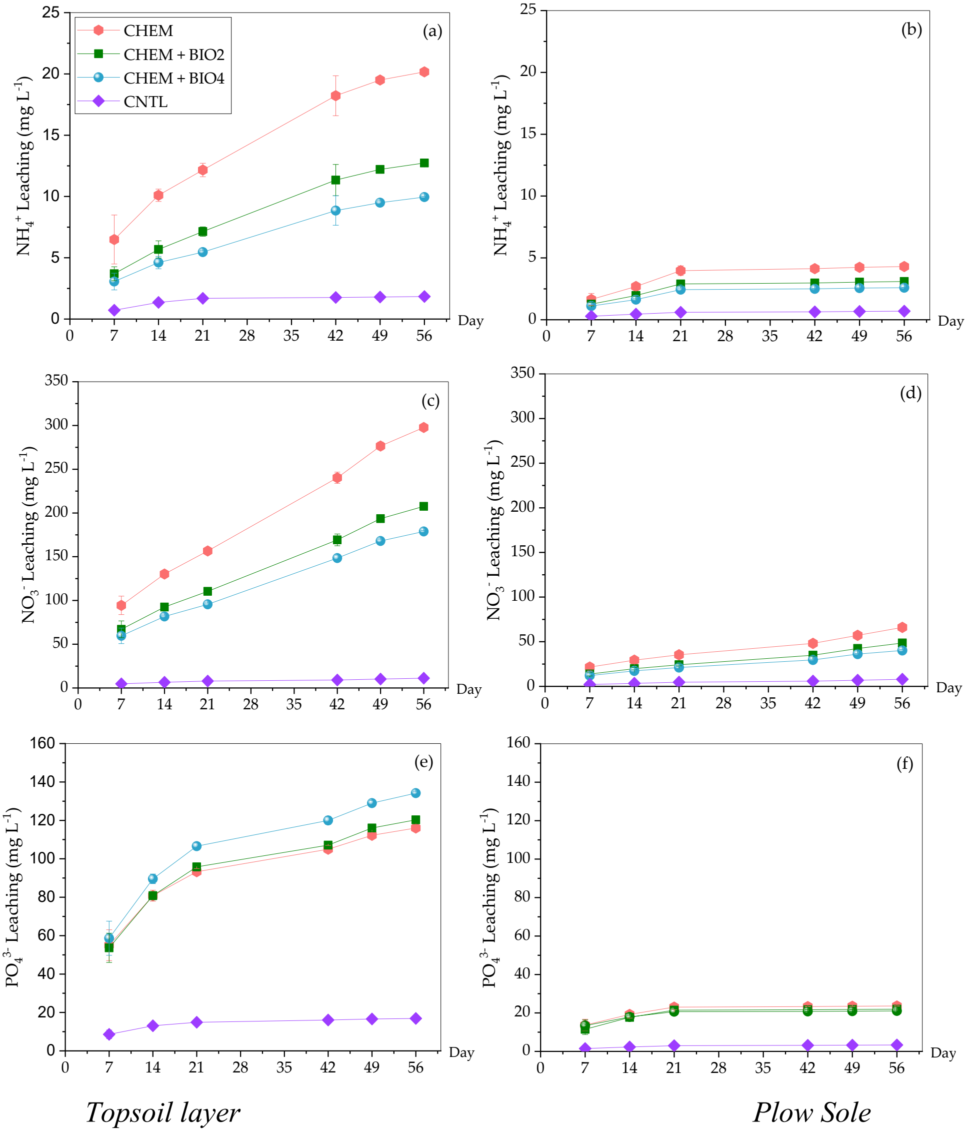


Figure 3-2: Mean values (± 1 SD, standard deviation) for the nutrient leaching (NH_4^+, NO_3^-, and PO_4^{3-}) (n = 12, each) through the topsoil layer and plow sole of soil columns. The graphs show their leachate accumulation at 7-day intervals: (a-b) ammonium (NH_4^+), (c-d) nitrate (NO_3^-), and (e-f) ortho-phosphate (PO_4^{3-}). CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + Biochar 2t ha^{-1}; CHEM + BIO4, CHEM + Biochar 4t ha^{-1}; CNTL, Control (no chemical and no biochar)

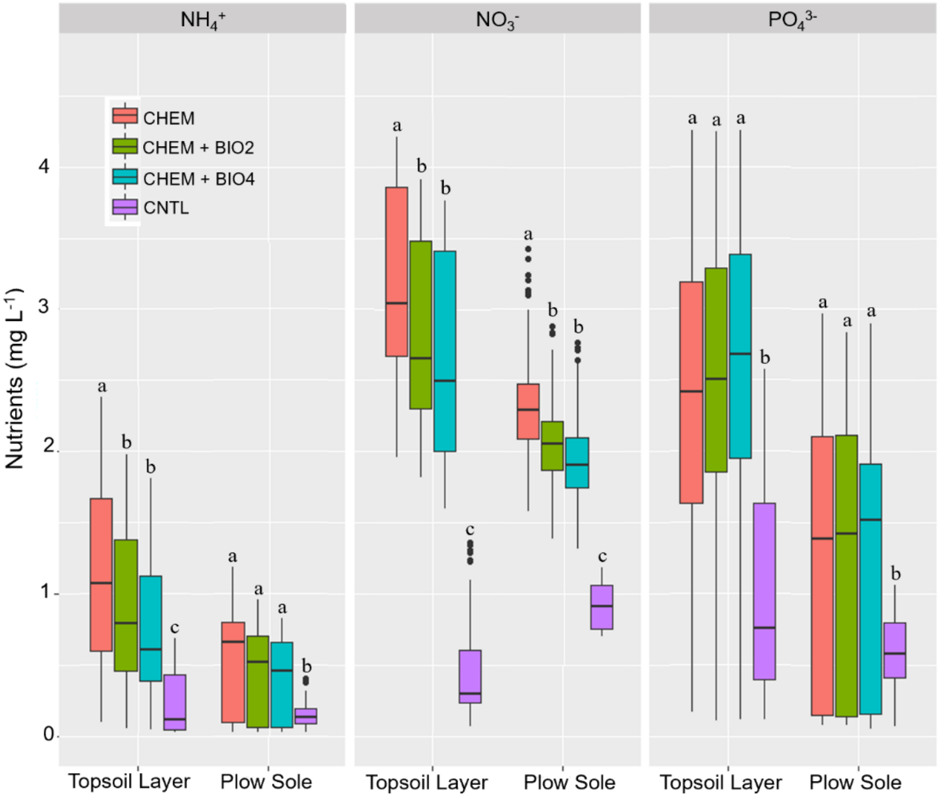
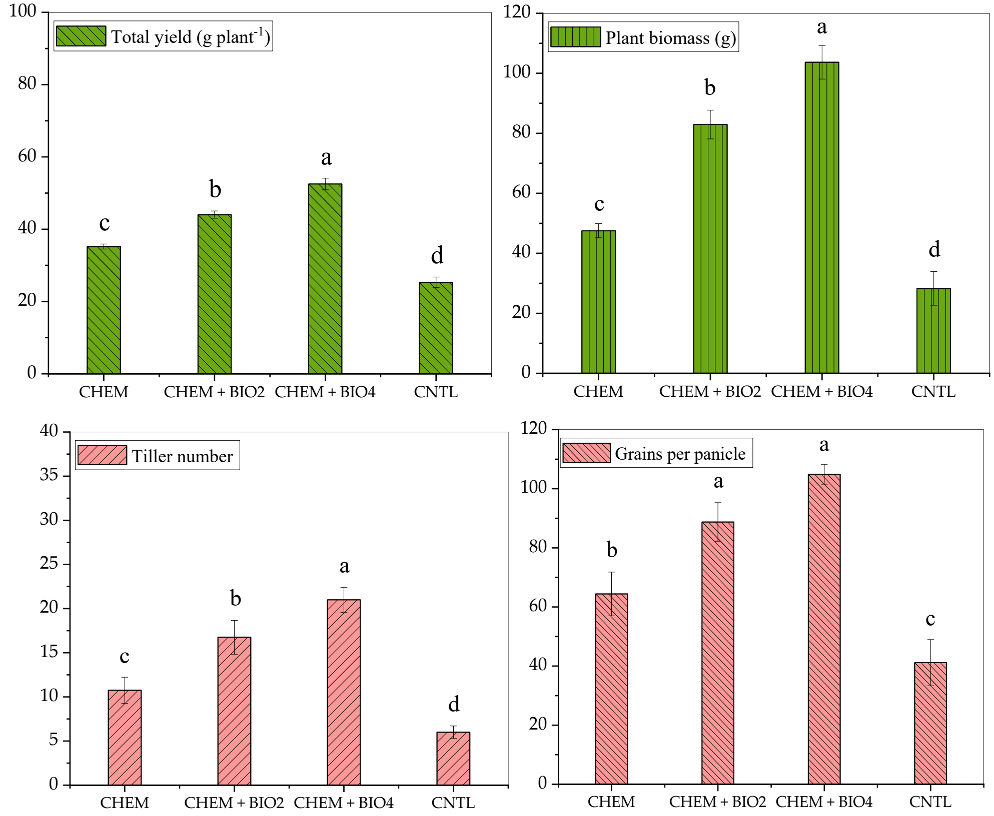


Figure 3-3: Boxplots showed the nutrient leaching through the topsoil layer and plow sole of the rice fields under different treatments. Mean values (± 1 SD, standard deviation) for NH_4^+, NO_3^-, and PO_4^{3-} (n = 12, each) were estimated from the reconstituted and conserved conditions for each soil layer. For the topsoil layer and plow sole of soil columns, the significant differences among treatments were analyzed using a one-way analysis of variance (one-way ANOVA) (Tukey's HSD test, $p < 0.05$), and were indicated by lower letters (a, b, c), in the soil-columns. CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + Biochar 2t ha^{-1}; CHEM + BIO4, CHEM + Biochar 4t ha^{-1}; CNTL, Control (no chemical and no biochar)

4.2. Rice growth and yield

The CHEM + BIO4 treatment, followed by CHEM + BIO2, resulted in the highest values for rice yield, plant biomass and tiller number ($p < 0.05$, Figure 3-4). On a percentage basis, for the rice yield, the CHEM + BIO4 treatment increased it by 16.14% compared to the CHEM + BIO2 treatment, 31.03% (CHEM), and 51.8% (CNTL) while, for the plant biomass, by 20% (CHEM + BIO2), 54.16% (CHEM), and 69.82% (CNTL). And, for the tiller number, the CHEM + BIO4 treatment increased it by 20.24% (CHEM + BIO2), 48.81% (CHEM), and 66.67% (CNTL). However, the two added biochar treatments enhanced the highest grains per panicle, and panicle length ($p < 0.05$, Figure 3-4). For the grains per panicle, the CHEM + BIO4 treatment increased it by 15.38% compared to the CHEM + BIO2 treatment, 25.86% (CHEM), and 49.65% (CNTL) while, for the panicle length, by 8.33% (CHEM + BIO2), 19.64% (CHEM), and 30.36% (CNTL).

Except for the root length, the CHEM + BIO4 treatment enhanced the highest values for the grain weight per panicle and root biomass ($p < 0.05$, Figure 3-4). For the grain weight per panicle, the CHEM + BIO4 treatment increased it by 15% compared to the CHEM + BIO2 treatment, 38.61% (CHEM), and 65% (CNTL) while, for the root biomass, by 18% (CHEM + BIO2), 48.11% (CHEM), and 66.46% (CNTL).



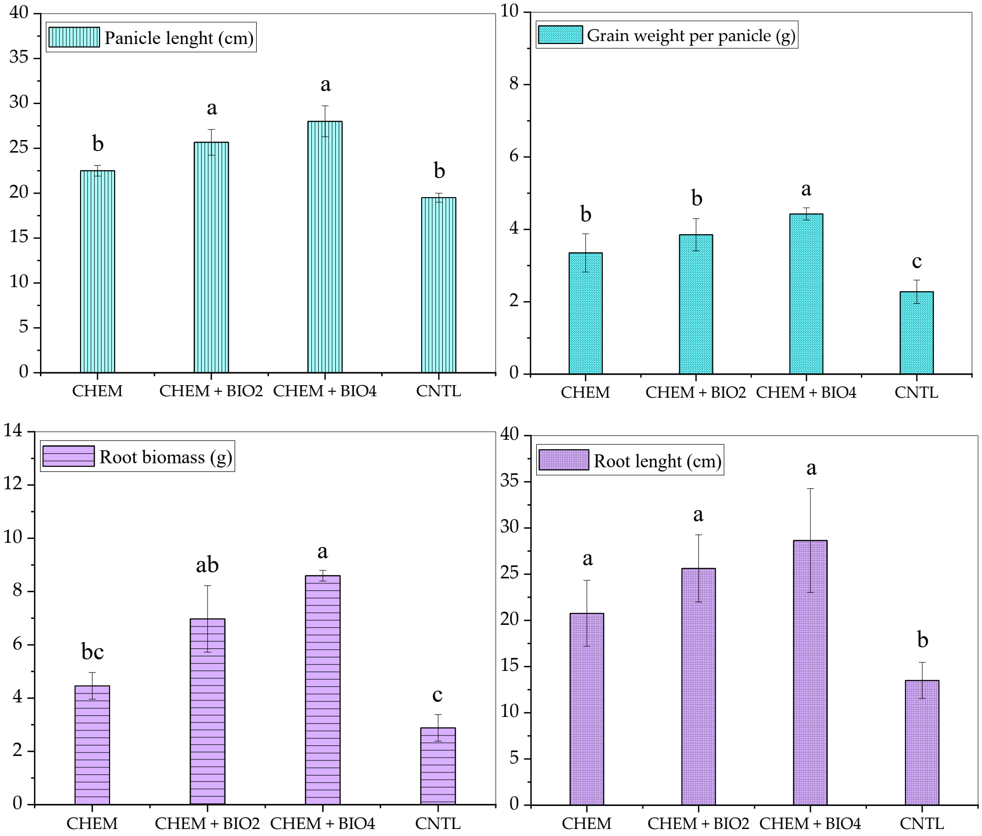


Figure 3-4: Mean values (± 1 SD, standard deviation) for Total yield (n = 4), plant biomass (n = 4), tiller number (n = 4), grains per panicle (n = 12), panicle length (n = 12), grain weight per panicle (n = 12), root biomass (n = 4), and root length (n = 12) were estimated from each treatment. The significant differences among treatments were analyzed using a one-way analysis of variance (one-way ANOVA) (Tukey's HSD test, $p < 0.05$), and were indicated by lower letters (a, b, c). CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + Biochar 2t ha-1; CHEM + BIO4, CHEM + Biochar 4t ha-1; CNTL, Control (no chemical and no biochar)

5. Discussion

In this study, soil bulk density (BD) of the topsoil layer and plow sole indicated their high values (i.e., Gleyic Acrisols with the soil BD of 1.60 g cm^{-3} and 1.92 g cm^{-3}; respectively) compared to that of the rice fields in Cambodia, and to that of sandy clay loam soil (about 1.45 g cm^{-3}) of Olubanjo and Yessoufou (2019). These authors reported that the soil BD is always altered in response to any compaction. In the rice fields, soil compaction can be associated with many field operations (e.g., passage of heavy machinery; (Shaheb et al. 2021)). These field operations often cause damage to the soil structure owing to pore space reduction (soil porosity) between soil particles (Singh et al. 2015). However, when soils containing more soil organic matter (SOM) tends to have less compaction (Athira et al. 2019), this conclusion was confirmed by the topsoil layer of this study Table 3-1. When having an increasing SOM in the soil layers, it has been widely credited for its inherent ability to improve the nutrient-holding capacity (e.g., NO_3^-, and Total N), thus reducing N leaching (Malcolm et al. 2019). The interactions of SOM and nutrient-holding capacity highlighted also less N leaching (NH_4^+, NO_3^-) in the topsoil layer and plow sole, especially when adding more biochar (Figure 3-2, CHEM + BIO4). As reported, when chemical fertilizers are combined with biochar the physical and chemical reactions which occur during the production of biochar granules slow the dissolution rate and extent of N compounds, compared to the chemical fertilizers alone, and reduce N leaching (Chen et al. 2018; Shi et al. 2020), and consequently increase rice growth and yield (Bai et al. 2022).

However, some of the nutrients (especially, N and P) released from chemical fertilizers can react with biochar pore surfaces (Haider et al. 2020; Hestrin et al. 2019; Joseph et al. 2018). Owing to its greater surface area, negative surface charge, and charge density, the biochar plays a role in reducing nutrient leaching, particularly immobilizing N (Lehmann et al. 2003), but not P (Figure 3-2), thus decreasing N-induced pollution in the environment (Huang et al. 2017a; Sun et al. 2018b). Ding et al. (2010) showed that the biochar could absorb ammonium ion (NH_4^+) by cation exchange and make the NH_4^+ content leach significantly different at different layers. Consistently, another study also highlighted that the average NH_4^+ leaching during the whole rice growth (i.e., Oryza sativa L. Nanjing 5055 and Oryza sativa L. Nanjing 9108) decreased in different soil layers (Zheng et al. 2019a). These conclusions were again confirmed by this study highlighting higher NH_4^+ leaching in the topsoil layer than in the plow sole (Figure 3-1 a, b). This could be also caused by the decreasing soil porosity, with its high soil BD, and higher water flow retention in the plow sole (see, Table 3-1). On the other hand, Knowles et al. (2011) found that the biochar decreased NO_3^- leaching from biosolid-amended soils (i.e., OM (Organic Matter) recycled from sewage and mixed with soil) to levels at/or below the control in their lysimeter experiment. Some mechanisms underlying this decreased NO_3^- leaching was the biochar ability which can absorb the NO_3^- content from the mixed soil. Previous studies also suggested that the biochar could be useful for reducing nitrogen leaching, including NH_4^+ and NO_3^- (Li et al. 2019b; Xu et al. 2014) while others suggested the biochar addition as a potential nutrient-retaining additive to increase the use efficiency of chemical fertilizers by rice growth, especially in the surface layer of soil (0–20 cm) like that of this study (Ding et al. 2010; Oladele et al. 2019; Selvarajh et al. 2021; Yang et al. 2015). Furthermore, a meta-analysis of Jeffery et al. (Jeffery et al. 2011) comprising 177 previous studies revealed that beneficial effects of biochar incorporation into soils outweighed negative and neutral effects, except that one study showed negative effects (Wang et al. 2016). For instance, an average increase of crop productivity of around 10% (i.e., rice wheat and corn) as an effect of biochar amendments was found. This appears that a small increase, owing to the wide range of biochar types and substrates, might occur in strongly varying conditions (Schulz et al. 2013).

In contrast to the NH_4^+ and NO_3^- leaching, Troy et al. (2014) and this study revealed that the wood and rice husk biochar did not reduce the PO_4^{3-} leaching, respectively, nor other studies showing that the biochar derived from various feedstocks (i.e., corn stover, oak wood, spruce, and scots pine) could not absorb the PO_4^{3-} leaching from an aqueous solution (Hollister et al. 2013; Soinne et al. 2014; Xu et al. 2014); and even more surprisingly, the biochar has the capability to increase the PO_4^{3-} leaching (Altland and Locke 2013; Nguyen et al. 2020). They have reported that the biochar produced from rice husk was a net PO_4^{3-} source, thus adding more PO_4^{3-} content to the soil layers. In addition, the added biochar might reduce the soil ability to absorb the PO_4^{3-} content (Cui et al. 2011; Soinne et al. 2014). And Pratiwi et al. (2016) observed that the biochar ability to absorb the PO_4^{3-} content was extremely limited, i.e., at a rate of 4% w/w in loamy soil, and even to solubilize some initial PO_4^{3-} contents below 60 mg L^{-1}.

Besides being useful for reducing nutrient leaching, many studies concluded that higher rice yield was recorded with the presence of any biochar (Chen et al. 2021a; Dong et al. 2015; Ghorbani et al. 2023; Xu et al. 2022; Yang et al. 2019), owing to its role in building soil fertility (Liu et al. 2021; Panhwar et al. 2020; Xu et al. 2016). For instance, Yin et al. (2021) found that their biochar treatment (4t ha^{-1}) significantly increased the rice yield. Their results were supported by this study with the same rate under the CHEM + BIO4 treatment (Figure 3-3). On the other hand, the combination of chemical fertilizers (30 kg ha^{-1}) with biochar (3-6t ha^{-1}) significantly affects the rice harvest index, yield, and biomass (Oladele et al. 2019). Together with increased rice yield and biomass, the biochar significantly enhanced tiller number (Chen et al. 2021a; Kamara et al. 2015; Oladele et al. 2019). Considered as the important traits for improving the rice yield (Liu et al. 2013), panicle length, grain weight per panicle, and grains per panicle were the highest in the presence of biochar while Yoo et al. (2014) showed an increased grains per panicle by 32.96% compared to the chemical fertilizers alone. In parallel, Singh et al. (2018) confirmed these increased panicle length and grain weight per panicle and suggested that the biochar can slowly release the inherent soil nutrients which can be used effectively by rice growth (Selvarajh and Ch'ng 2021). However, there was no significant difference between the chemical fertilizers and biochar improving root biomass and root length. Consistently, Pratiwi and Shinogi (2016) showed that the biochar only slightly increased root biomass and root length. Liu et al. (2021) found that the effects of biochar on root growth were not always synchronized, but mostly depending on the soil nutrient conditions and rice growth stages (Biederman and Harpole 2013a). For instance, as seen in stage 2 (i.e., tillering starting from 1 month) in the study of Joseph et al. (2021), the rice roots intercept and interact with any biochar.

6. Conclusion

Current research efforts focusing on chemical fertilizers leaching, from agricultural production, into the environment are still very few in Cambodia. Several enhanced nutrient techniques in the soils were proposed in many studies, but in this study the combination of chemical fertilizers with a rice husk biochar might be plausible for consideration in the country, owing to low-cost production of the biochar, and easy-to-use, compared to the chemical fertilizers alone. These combined treatments revealed a high efficiency in reducing the NH_4^+ and NO_3^- leaching in the soil group considered (i.e., Gleyic Acrisols under the CHEM + BIO4 treatment), thus increasing soil water-holding capacity, nutrient availability, and uptake (Selvarajh and Ch'ng 2021; Shi et al. 2020), and enhancing rice growth and yield. In contrast, with the presence of biochar, the PO_4^{3-} leaching was not reduced, suggesting an ion strength, soil texture, soil pH, and added biochar rates should be involved with studying soil, fertilizer, and biochar interactions (Kang et al. 2011). Interestingly, within these gaps, lower biochar rates should be assessed to minimize (chemical) fertilizers leaching, in different soil groups under different irrigated conditions, because while being at the two rates of 1% w/w and 3% w/w, the rice husk biochar decreased NO_3^- leaching in the clay soil more than in the loamy sand (Liu et al. 2013). And the rice yield with added biochar, at the two rates of 20t ha^{-1} and 40t ha^{-1}, was measured about 15.53% and 24.43%, respectively, higher than that with non-biochar under water-saving irrigation method (Chen et al. 2021a).

Chapter 4

Combined Effects of Biochar and Chemical Fertilizers on Rice Yield, Quality, and Nutrient Loss in Cambodian Soils nder Various Irrigation Method

The content of this chapter has been published in the **Journal of Soil Science and Plant Nutrition**: Chenda Lai, Sarith Hin, Pinnara Ket, Juthamas Chaiwanon, Aurore Degré, and Vannak Ann. *Combined Effects of Biochar and Chemical Fertilizers on Rice Yield, Quality, and Nutrient Loss in Cambodian Soils Under Various Irrigation Methods*, **Journal of Soil Science and Plant Nutrition**, (2026). https://link.springer.com/article/10.1007/s42729-026-03046-6

Prelude explaining the importance of this chapter in relation to the study's Objectives:

This study aims to evaluate the combined effects of rice husk biochar and chemical fertilizers on rice yield, grain quality, and nutrient loss under different soil types and irrigation regimes in Cambodia. Specifically, it investigates how varying biochar application rates (4 and 6 t ha^{-1}) influence productivity and nutrient retention in clay and sandy loam soils. The research also examines whether biochar can offset yield reductions often associated with water-saving irrigation methods like Alternate Wetting and Drying (AWD). By conducting soil column experiments, the study seeks to generate precise data on nutrient leaching patterns, plant growth, and grain composition. Ultimately, the objective is to determine optimal biochar application strategies that enhance rice yield and quality while minimizing environmental risks.

Abstract

Rice production in Cambodia faces challenges due to water scarcity and improper fertilizer use, which raise environmental concerns. Integrating biochar and water-saving irrigation methods offers a promising solution for farmers. This study evaluated how biochar and chemical fertilizers affect rice yield, quality, and nutrient loss under different soil types and irrigation methods. A column experiment was conducted using clay (S1) and sandy loam (S2) soils, with two irrigation methods: alternate wetting and drying (AWD) and continuous flooding (CF). The treatments included a control (T0), chemical fertilizer only (T1), chemical fertilizer supplemented with 4 tons per hectare (t ha^{-1}) of biochar (T2), and chemical fertilizer supplemented with 6 t ha^{-1} of biochar (T3). Across both soil types and irrigation methods, T3 resulted in the highest dry grain yield and protein content compared to T1. This biochar at 6 t ha^{-1} was effective in both clay and sandy loam soils, though its efficiency varied slightly; for instance, under AWD irrigation, rice yield increased by approximately 35% in sandy loam and 40% in clay soil. Biochar application at 6 t ha^{-1} significantly reduced the leaching of NO_3^-, NH_4^+, and PO_4^{3-} compared to other treatments. Although there were no significant differences in amylose content among the treatments, biochar application positively influenced plant biomass and chlorophyll content. These results show that increasing the biochar rate from 4 to 6 t ha^{-1} further enhances rice yield and protein content without affecting amylose content, while both rates reduce nutrient leaching and contribute to more sustainable farming practices.

1. Introduction

Rice is considered the backbone of Cambodian cuisine. Recently, the Royal Government of Cambodia has been promoting the sustainable production of high-quality rice through environmentally friendly agricultural methods (Khema et al. 2022). With the improvement in people's living standards, the demand for high-quality rice has grown significantly, focusing on both quantity and quality (Cheng et al. 2019; Su et al. 2019). According to the Cambodia Agriculture Survey 2023, the average rice yield was 3.14 t ha^{-1} for non-aromatic varieties and 2.62 t ha^{-1} for aromatic varieties, reflecting differences by rice type and agro-ecological zone (NIS 2023b). The yield limitation stems from challenges such as poor irrigation systems, soil degradation, drought, and high costs of production and fertilizers (Touch et al. 2024). However, infrastructure for irrigation development remains limited, leading to persistent water shortages during the dry season (Sithirith 2021). In 2023-2024, dry-season rice occupied around 19% of total paddy land, with some farmers continuing to cultivate despite concerns over water scarcity (Touch et al. 2024). While awareness of water-saving methods is growing, many smallholder farmers still face challenges in accessing water and efficient management knowledge (Hoogesteger et al. 2023; McPhee et al. 2022).

Another significant challenge is fertilization, including the overuse or underuse of chemical fertilizers (Kong et al. 2020a). Cambodia’s use of synthetic fertilizers remains widespread, with 63.9% of agricultural holdings applying them, particularly in rice cultivation (NIS 2023b). Average application rates for rice are estimated at 180 kg ha^{-1}, varying by rice cultivar and agro-ecological zone; non-aromatic varieties typically receive higher inputs, and irrigated systems generally achieve greater productivity than rainfed lowlands (NIS 2023b). Prolonged use of chemical fertilizers harms soil quality by decreasing organic matter and increasing pollution (Chen et al. 2024). Additionally, excess phosphorus (P) can leach into groundwater, increasing the risk of eutrophication in nearby water bodies, especially in sandy soils or areas with tile drainage (Wurtsbaugh et al. 2019). Among the nutrient anions, nitrate (NO_3^-) is the most easily leached because of its negligible reaction with the soil matrix and, therefore, is very mobile in various soil types (Dou et al., 2016; Zhao et al., 2021). Notably, sandy soil, known for its high permeability and susceptibility to nutrient leaching, is the most abundant soil group for rice cultivation in Cambodia, as classified under the Cambodian Agronomic Soil Classification (CASC) (White et al. 2006). The Prateah Lang and Bakan soils, although infertile, present fewer constraints to rice production and are widespread, occurring on about 45% of the rice-growing area. Hence, quantifying N and P loss through surface runoff and leaching is essential to optimize fertilization practices (Hua and Zhu 2020).

Due to these pressing issues, there is an urgent need to improve sustainable practices and enhance water productivity in rice production, ensuring higher yields while optimizing water use efficiency. Introducing water-saving irrigation methods, such as alternative wetting and drying (AWD), along with incorporating soil amendments, can enhance water productivity and reduce fertilizer loss. While AWD may occasionally cause minor yield losses, combining it with soil amendments can maintain the yield by improving water retention, nutrient release, and uptake (Haque et al. 2022a). Applying soil amendments like rice husk biochar has been introduced recently for soil improvement (He et al. 2022). Rice husk biochar (RHB) is a cheap and renewable material that is rich in carbon and has many tiny holes, making it useful for cleaning up water and soil (Na et al. 2025; Ullah et al. 2024). In Cambodia, rice husk is primarily used for energy production, with a portion remaining unused (Nam et al. 2024a). Additional residues such as cassava stems, corn stover, and mango seeds are widely available and often considered waste. Medium-scale kilns yield 7–15 kg per run, and larger systems up to 400 kg, making biochar application practical for local farmers[1], except when sourcing certified carbon-grade products, which are typically more expensive.

Biochar can retain nutrients (N and P), improve soil properties, and enhance phosphorus utilization rates (Bian et al. 2016; Glaser and Lehr 2019; Liu et al. 2016a; Shi et al. 2020; Yang et al. 2021). Under different irrigation methods, such as AWD, biochar helps maintain soil moisture and nutrient availability, mitigating the negative effects of water stress on rice growth. Research indicates that biochar application under AWD irrigation can increase rice yield by up to 12.5%, improving nutrient uptake and water-use efficiency (Chen et al. 2021b) . Biochar not only improves soil nutrient retention but also plays a crucial role in enhancing rice yield (Agarwal et al. 2022) and grain quality, including protein content (Ali et al. 2020a), but its effectiveness varies with biochar rate, soil type, climate, and experimental conditions (Chen et al. 2023b; Ma et al. 2019; Munda et al. 2018). Lai et al. (2024) investigated biochar application rates of 2 t ha^{-1} and 4 t ha^{-1}. While 4 t ha^{-1} showed promising results in reducing nitrogen leaching, it did not significantly reduce phosphorus loss.

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[1] Chan Saruth. *Biochar Production Technology in Cambodia*. Presentation at the UN-CSAM Regional Workshop on Sustainable Agricultural Mechanization, 2020. Available at PowerPoint 演示文稿.

However, in Cambodia, scientific studies on the effects of biochar on rice yield and nutrient loss under different irrigation methods are limited. Specifically, there is a lack of studies on water management practices such as alternative wetting and drying (AWD) and continuous flooding (CF) when combined with biochar incorporation in rice cultivation and quality (Ballester et al. 2021a; Becker et al. 2023). Thus, the objectives of this study were to evaluate the effect of biochar and application rate incorporated with chemical fertilizer on rice productivity, quality, and nutrient loss via leaching for clay soil and sandy loam under irrigation methods (i.e., CF and AWD) using the soil column experiment. Rice husk biochar is hypothesized to improve rice productivity and quality while reducing nutrient loss via leaching. These effects may vary with biochar application rate, soil type, and irrigation methods, with biochar potentially offsetting AWD-induced yield reductions by improving nutrient availability and soil conditions.

2. Material and method

2.1. Biochar and soil sample

Biochar used in this study was a local product derived from rice husk using the protocol described in Lai et al. (2023). The biochar characteristics were analyzed before experimenting, including electrical conductivity (EC) (µS cm^{-1}) and pH (1:5 H_2O) soil/water suspension method (Rayment and Higginson 1992). Total carbon was determined using an elemental analyzer (Flash 2000, Thermo Fisher, USA). The organic matter (OM) (%) was measured with the Walkley-Black method (Gupta 2014). Total N (g kg^{-1}), NO_3^- (mg L^{-1}), and NH_4^+ (mg L^{-1}) contents were measured with Kjeldahl method (Baethgen and Alley 1989; Bremner 2016; Gupta 2014), whereas available P (mg kg^{-1}) was measured.

The two soils selected for this study are the most abundant among the 11 soil groups for rice cultivation in Cambodia, with 10-15% (Bakan) and 25-30% (i.e., Prateah Lang), respectively (White et al. 1997). Specifically, the soil "Bakan (S1) was classified by the FAO/UNESCO as Luvisols (White et al. 2006) , while the soil "Prateah Lang (S2)" as Gleyic Acrisols (Ballester et al. 2021). The S1 and S2 soil samples were selected in triplicate at three different sampling locations (i.e., up to horizon B as defined by the FAO Guidelines for Soil Description (FAO 2006) (FAO 2006).

Before the experiment, the initial samples of both soil types were analyzed to determine different physicochemical properties, including pH, EC (uS cm^{-1}), soil organic carbon (%), soil organic matter (SOM) (%), bulk density (BD) (g cm^{-3}), Total N (%), NO_3^- (mg 100 g^{-1}), NH_4^+ (mg 100 g^{-1}), available P (mg L^{-1}), exchangeable K (cmol kg^{-1}), CEC and soil texture. Soil pH, EC, BD, organic matter, Total N, NO_3^-, NH_4^+, available P, exchangeable K, and CEC were analyzed following the same methods used for the biochar properties. In addition, soil organic carbon was analyzed using the Walkley-Black method, while the soil texture was determined by the hydrometer test (USDA) (Gee & Or, 2002).

The basic characteristics of biochar and soil as measured from the two soil types (i.e., clay and sandy loam) are summarized in Supplementary Table S1 or Annex 5. The EC of biochar was 57.27 ± 1.17 µS cm^{-1} with an alkaline pH of 8.43 ± 0.09. The total carbon, organic matter, and SSA were considered high, with values of 54.07 ± 3.41 %, 64.88 ± 4.09 %, and 102.20 ± 3.80 m^2 g, respectively. The clay soil had significantly higher values of soil EC, organic carbon, organic matter, total N, available P, exchangeable K, and CEC compared to the sandy loam. The pH of the clay was also significantly higher than that of the sandy loam. However, neither NO_3^- nor NH_4^+ values for the two soil types were significantly different.

2.2. Soil column design

Soil columns of clay (S1) and sandy loam (S2) were collected directly from the field under undisturbed conditions to preserve the original soil structure. A thick-walled PVC pipe (5 mm wall thickness, 65 cm length, and 15 cm diameter) was used for sampling (Supplementary Fig. S1a or Annex 6). Then, the columns were installed in a greenhouse. To collect the leachate, a hole was drilled at 30 cm depth (from the top, because we keep 10 cm empty for irrigation), one at 45 cm depth, and the last at 65 cm depth (bottom) for the percolation. To prevent sedimentation disruption, the two holes were covered with a nylon mesh and fitted with faucets. The percolation was collected at the bottom of the column by removing a tiny piece of soil and inserting sand and gravel above a third faucet. About 20 cm long and 5cm wide, a transparent wall was built to monitor the water level and root growth. Three sets of soil column samples represent the soils for rice paddy in Cambodia (i.e., S1 and S2) (Supplementary Fig. S1b or Annex 6) and under two irrigation methods: alternative wetting and drying (AWD) and continuous flooding (CF).

2.3. Soil preparation and treatments

The experiment consisted of four treatment groups: T0 served as the control, with no chemical fertilizer or biochar; T1 included chemical fertilizers which is urea (46% N), diammonium phosphate (DAP; 18% N, 46% P_2O_5), and potassium chloride (KCl; 50% K); T2 combined T1 with biochar at a rate of 4 t ha^{-1}; and T3 combined T1 with biochar at 6 t ha^{-1}. Fertilizer application was split into two stages: the first during soil preparation (urea, DAP, and KCl), and the second at the booting stage (urea and DAP only), with a total input of 133 kg N ha^{-1}, 46 kg P_2O_5 ha^{-1}, and 30 kg K_2O ha^{-1}. This chemical fertilizer was applied to approximately 3.7 kg of topsoil of the column, resulting in total nutrient inputs equivalent to 63.5 mg N kg^{-1}, 35.5 mg P kg^{-1}, and 11.86 mg K kg^{-1} of soil. In addition, before rice sowing, biochar was added to the corresponding soil column and mixed into the top 10-15 cm soil layer as an amendment with 0.706 g for T2 and 1.06 g for T3.

The four treatments were applied to the two soil types (i.e., the clay (S1) and sandy loam (S2). An alternative wetting and drying (AWD) method was applied to the two soil types (S1 and S2). In contrast, the continuous flooding (CF) method was only applied to S2 (Supplementary Fig. S1b or or Annex 6) due to resource limitations. Three replications of each soil column were prepared, along with additional columns set aside for variable measurements at the tillering, flowering, and harvesting stages. A rice cultivar (locally named OM 5451) was selected for the direct seeding method.

2.4. Irrigation management

For the continuous flooding (i.e., CF) irrigation, a continuous ponded layer of water, approximately 10 cm deep, was maintained over the soil surface throughout the entire rice-growing period. For alternative wetting and drying (i.e., AWD), after the column was initially flooded, it was allowed to dry until the ponded water level reached approximately -15 cm below the soil surface. This drying period was followed by another flooding event, repeating the cycle. The total water requirements for each irrigation were recorded for the whole period. For AWD, the total water irrigated was about 15,000 mL for S1 and 18,000 mL for S2, while it was 24,000 mL for CF.

2.5. Rice yield and quality

Dry grain yield (g plant^{-1}) was measured at the harvesting stage. For the grain quality assessment, after harvesting, the grains were carefully threshed, cleaned, air-dried to a constant weight, and stored at ambient temperature before grain quality analysis. Total protein (µg L^{-1}) was estimated by modifying Lowry's method given by (Hartree 1972) Hartree (1972). The contents were mixed well, and a spectrophotometer measured the absorbance at 650 nm after 15 minutes. The amylose content (%) of milled rice was determined using the colorimetric iodine assay index method. The values for absorbance were plotted at 620 nm against the concentration of anhydrous amylose (mg), and the conversion factor was determined.

2.6. Rice growth and plant nutrient content

Triplicate rice samples were measured for plant biomass (g $plant^{-1}$), root biomass (g), and chlorophyll at each tillering stage, flowering, and harvesting stage from the spared column. The soil column was carefully broken to keep the root structure. The dried weight of straw, leave, and root was determined after oven-drying at 70 °C to a constant weight for 48 hours.

The leaves of rice plants were analyzed for NO_3^-, NH_4^+, and PO_4^{3-} contents at the tillering, flowering, and harvesting stages. Dried leaves were ground into a powder, weighed, and used for extraction. NO_3^-, NH_4^+, and PO_4^{3-} contents were determined using colorimetric assays: NO_3^- by the salicylic acid method (Zhao and Wang 2017), NH_4^+ by the Bertholet reaction (Bräutigam et al. 2007), and PO_4^{3-} by the molybdenum blue assay (Pinit et al. 2020). Concentrations were calculated from absorbance values relative to a standard curve, expressed as micrograms per gram dry weight (µg g^{-1}).

2.7. Measuring soil nutrient leaching

Each week, 50 mL of leachate was sampled from each port 1 and port 2 using sampling bottles (polypropylene material) to track the nutrient content in each layer. Percolation water (i.e., port 3) was allowed to drain freely to observe the nutrient loss through the vertical condition (Zheng et al. 2019b) and the volume was recorded at 7-day intervals. The leachate samples were measured immediately for nitrate (NO_3^-) (mg L^{-1}) and ammonium (NH_4^+) (mg L^{-1}) with the Vario Tube Test, and ortho-phosphate (PO_4^{3-}) (mg L^{-1}) with the ortho method with tablets. All three variables were measured using a photometer (Part Number 214020, MD600, Lovibond, Germany). The leachate sample was also analyzed for pH value using a pH meter (Thermo Scientific™, 9617BNWP, Lenexa, US).

3. Data analysis

All statistical analyses were conducted using R (R Core Team 2021). A one-way analysis of variance (ANOVA) (Tukey's HSD test, $p < 0.05$) was used to see how chemical fertilizers and their mix with biochar affected nutrient loss through leaching in two types of soil, and to find out how different treatments improved all the factors related to rice growth, yield, nutrition, and quality. The important differences in the factors related to biochar and the two soil types, calculated using the T-test for comparing averages, were significant at the $p < 0.05$ level. Principal Component Analysis (PCA) was conducted to examine the relationships between different treatments and their impact on rice growth, yield, and nutrition using the ade4 and FactoMineR packages in R. Biplots were generated with confidence ellipses at a 95% confidence level and color coding to distinguish between treatments.

4. Results

4.1. *Effect of biochar on rice yield and quality*

The yield and quality of the rice showed a marked enhancement following the biochar application, as illustrated in Figure 4-1. The dry grain yield and total protein in rice were significantly the highest for chemical fertilizer + biochar 6 t ha^{-1} (T3), followed by chemical fertilizer + biochar 4 t ha^{-1} (T2), chemical fertilizer (T1), and control (T0), for both soil types (i.e., the clay (S1) and sandy loam (S2)) and irrigation methods (i.e., AWD and CF) ($p < 0.05$) (Figure 4-1a, b). For the quantity basis of dry grain yield, T3 increased by 40% compared to T1 in S1_AWD, 35% (S2_AWD), and 37% (S2_CF), respectively. In addition, for total protein, T3 increased by 20% compared to T1 in S1_AWD, 18% (S2_AWD), and 19% (S2_CF). However, there was no significant difference in amylose content among all the treatments for both soil types and irrigation methods (Figure 4-1c).

4.2. *Effect of biochar on rice growth and plant nutrients*

Figure 4-1 shows the impact of various treatments on rice growth, including total plant biomass, root biomass, and chlorophyll, across two soil types and irrigation methods: clay (S1) and sandy loam (S2), as well as AWD and CF. For total plant biomass and root biomass, there was no statistically significant difference between biochar rates of 4 t ha^{-1} (T2) and 6 t ha^{-1} (T3) in either soil type or irrigation method (Figure 4-1d, e). This suggests that increasing biochar beyond 4 t ha^{-1} may not yield additional biomass benefits under the tested conditions. In addition, the S2_AWD for chlorophyll (Figure 4-1f) showed notable differences only between treatments, T3 and T0.

For NO_3^- and NH_4^+ content in leaves, T0 was the lowest, while there was no significant difference between T1, T2, and T3 for both soil types and irrigation methods (Figure 4-1g, h). However, for PO_4^{3-} content in leaves, T3 was significantly the highest, followed by T2, T1, and T0 for both soil types and irrigation methods ($p < 0.05$). Furthermore, there was no significant difference between T1 and T2 for this variable (Figure 4-1i).

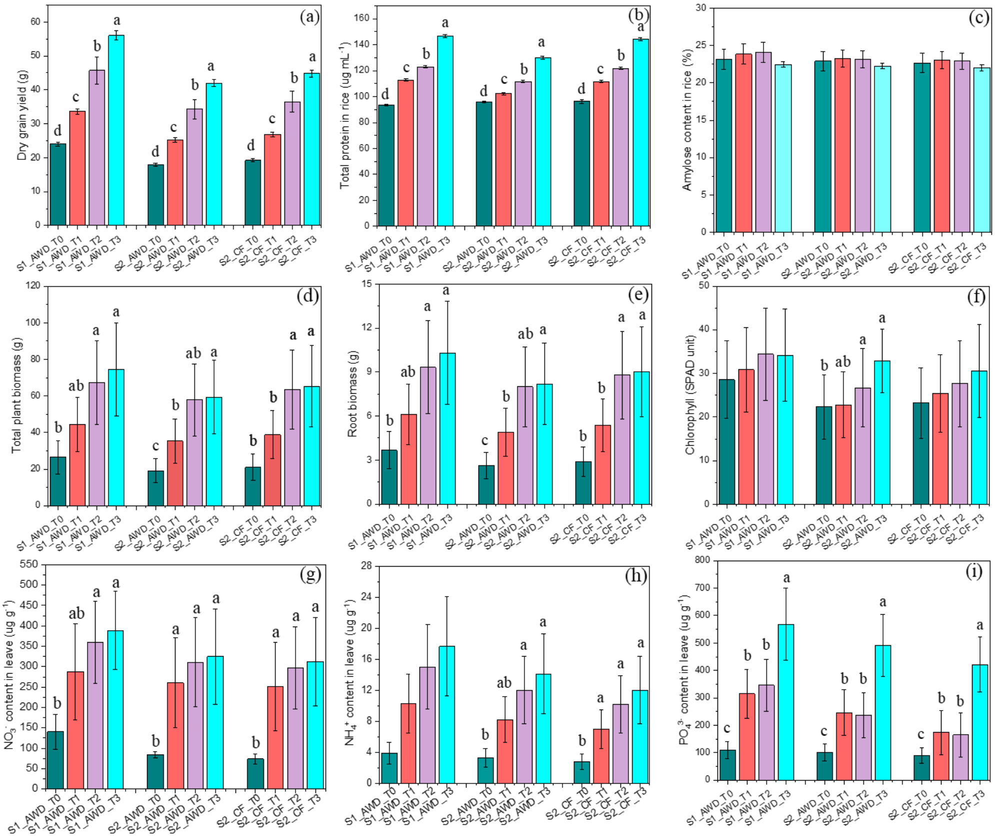

Figure 4-1: Mean values (± 1 SD, standard deviation) for: (a) dry grain yield (n = 3), (b) total protein (n = 3), (c) amylose content (n = 3), (d) total plant biomass (n = 9), (e) root biomass (n = 9), (f) chlorophyll (n = 9), (g) NO_3^- content in leave (n = 9), (h) NH_4^+ content in leave (n = 9), (i) PO_4^{3-} content in leave (n = 9) were estimated from each treatment. The significant differences among treatments were analyzed using a one-way analysis of variance (ANOVA)

(Tukey's HSD test, $p < 0.05$) and were indicated by lower letters (a, b, c). T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, DAP, and KCl; T2 combined T1 with biochar at a rate of 4 t ha^{-1}; and T3 combined T1 with biochar at 6 t ha^{-1}. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding.

4.3. Principal Component Analysis

Principal Component Analysis (PCA) was used to look at how plant nutrient content, rice growth, yield, and quality are related under different treatments for both soil types and irrigations (Figure 4-2). The first two components (Dim1 (79.1%) and Dim2 (12.5%)) explain 91.6% of the total variance. The dry grain yield, total protein, NH$_4^+$ content in leaves, and PO$_4^{3-}$ content in leaves were positively correlated with each other, and this reflects increased variability in the presence of biochar at a rate of 6t ha^{-1} (T3) in both soil types and irrigation methods. In contrast, control treatments, including S1_AWD_T0, S2_AWD_T0, and S2_CF_T0, were observed to be farther from these variables. Conversely, amylose content showed a negative correlation with higher biochar; thus, it is higher in the treatment without biochar (i.e., S1_AWD_T1).

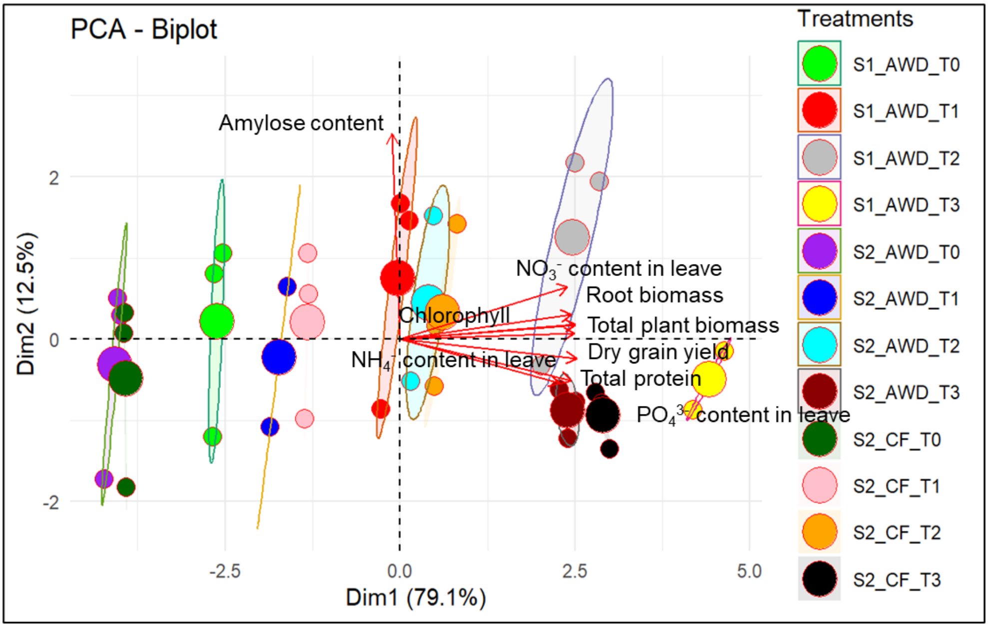

Figure 4-2: PCA biplot depicting the relationship between the estimated variables and treatments. PC1 on the x-axis accounted for 79.1% of the total variables, while PC2 explained 12.5% of total variability and is shown on the Y-axis. The different colors represent the treatments. T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of

chemical fertilizers including urea, diammonium phosphate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha^{-1}; and T3 combined T1 with biochar at 6 t ha^{-1}. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding.

4.4. Effect of biochar on N and P loss

A mean comparison of the time effect on the NO_3^- loss accumulation from the vertical percolation port was presented in Figure 4-3. During the experiment, NO_3^- loss accumulation increased significantly and almost continuously, reaching a steady rate in the last two weeks. The total NO_3^- loss accumulation was higher in chemical fertilizer treatment (T1) for both soil types and irrigation method (i.e., 78.1 mg, 94.8 mg, 115.8 mg) in S1_AWD, S2_AWD, and S2_CF, respectively (Figure 4-3a, b, c). In the same order for NH_4^+ loss accumulation, the higher T1 values were 16.9 mg, 20.7 mg, and 25.6 mg (Figure 4-3d, e, f). In addition, for PO_4^{3-} loss accumulation, T1 were 10 mg, 9.1 mg, and 10.9 mg, and it decreased to 6.81 mg, 5.91 mg, and 7.62 mg for T3 in S1_AWD, S2_AWD, and S2_CF, respectively.

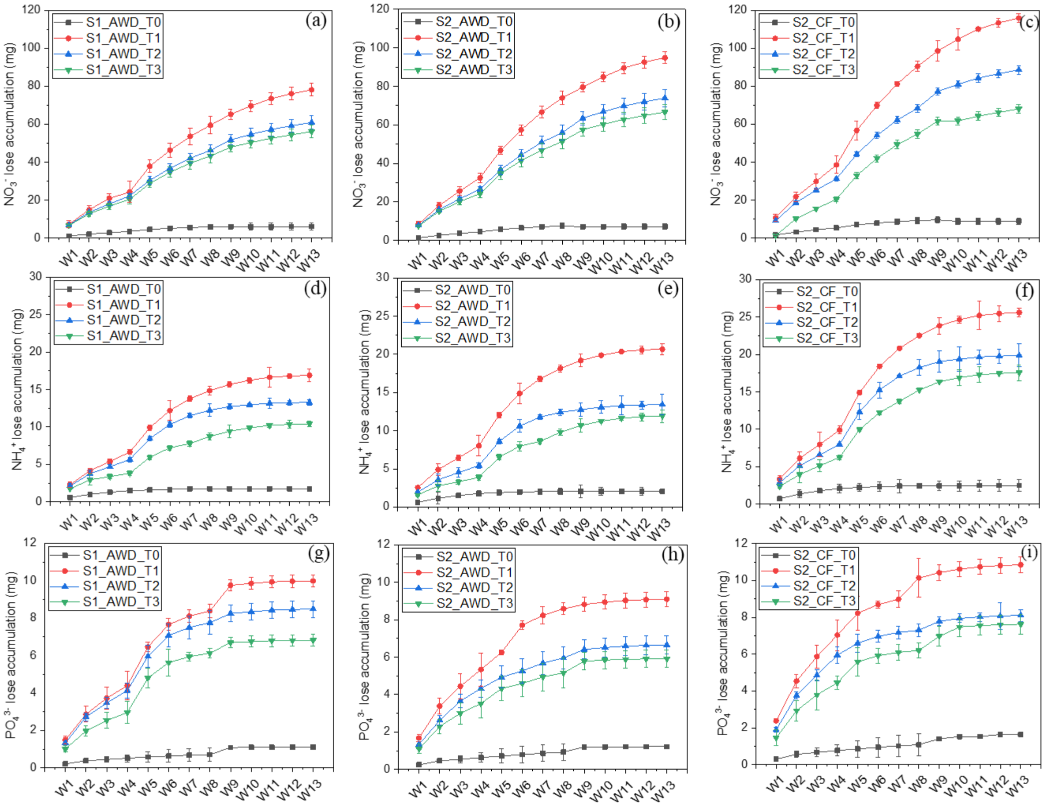

Figure 4-3 : Mean values (± 1 SD, standard deviation) for weekly loss accumulation for: (a, b, c) NO_3^- , (d, e, f) NH_4^+, and (g, h, i) PO_4^{3-} (n = 3, each). T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, diammonium phosphate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha⁻¹; and T3 combined T1 with biochar at 6 t ha⁻¹. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding.

The statistical significance *($p < 0.05$)* of nutrient leaching across treatments is illustrated in Figure 4-4. The control (T0), which received no chemical fertilizer or biochar, consistently showed the lowest leaching values across all nutrients. Among the biochar treatments, only T3 significantly reduced NO_3^-, NH_4^+, and PO_4^{3-} leaching compared to T1 across both soil types and irrigation methods. T2 did not differ significantly from T3 for NO_3^- and NH_4^+, and showed no significant differences from either T1 or T3 for PO_4^{3-}.

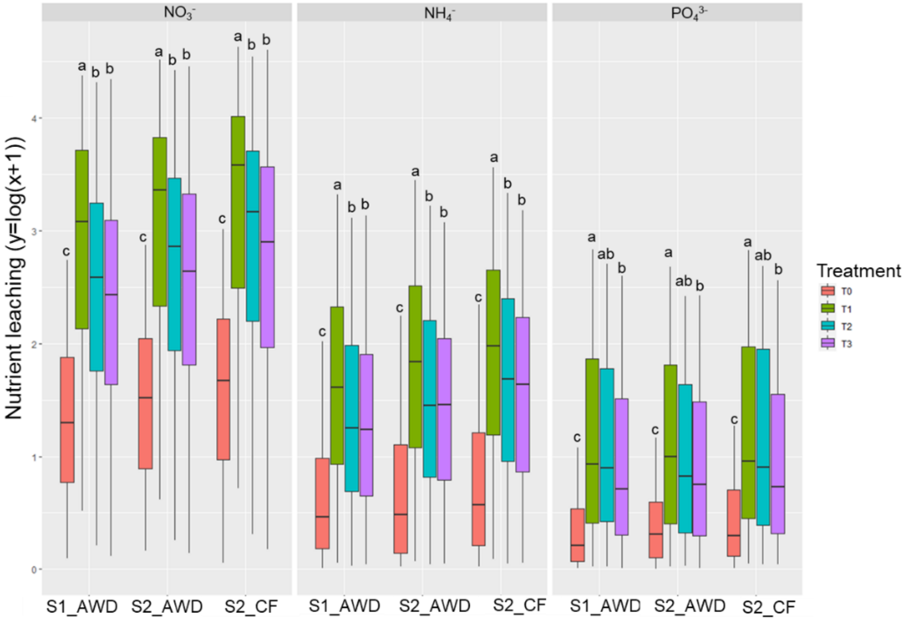

Figure 4-4 : Boxplots showed the nutrient leaching under different treatments. Mean values (± 1 SD, standard deviation) for NO_3^-, NH_4^+, and PO_4^{3-} (n = 117 each) were estimated from 3 ports of the 13 weeks. Nutrient leaching (y) was log-transformed ($y = \log(x + 1)$), and x represents each nutrient leaching variable (mg L-1). For each condition, the significant differences among treatments were analyzed using a one-way analysis of variance (ANOVA) (Tukey's HSD test, $p < 0.05$) and were indicated by lower letters (a, b, c) in the soil columns. T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, DAP, and KCl; T2 combined T1 with biochar at a rate of 4 t ha^{-1}; and T3 combined T1 with biochar at 6 t ha^{-1}. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding.

5. Discussion

The present study found that biochar application at the highest rate of 6 t ha^{-1} (i.e., T3) significantly enhanced rice yield and rice growth (i.e., total plant biomass, NH_4^+, NO_3^-, and PO_4^{3-} content in leaves) in both clay (S1) and sandy loam soil (S2) (Figure 4-1). However, the effectiveness of biochar is influenced by soil texture, irrigation method, and application rate, leading to variations in yield improvement ranging from 10% to 30% (Abbas et al. 2024; Asadi et al. 2021; Nam et al. 2024b). In clay soils, biochar’s alkaline pH and high cation exchange capacity (CEC) promote nutrient retention, particularly ammonium ions, while its fine particle structure improves soil aggregation and aeration (Demirkaya et al. 2025). In sandy loam, biochar’s porosity and water-holding capacity help reduce rapid nutrient leaching and improve moisture availability, compensating for low native fertility (Li et al. 2021). Specifically, these results showed that clay soil (S1_AWD_T3) provided a higher dry grain yield compared to other treatments, highlighting the influence of soil texture on biochar effectiveness. While the AWD irrigation method combined with biochar showed water savings and maintained high yields, the CF method also provided substantial benefits. These differences were mainly caused by the type of soil, the irrigation method used, and how much biochar was applied, all of which affected how well nutrients were kept in the soil and how efficiently water was used, leading to better rice production (Chen et al. 2021b) . Under AWD, biochar's porous matrix retains nutrients during dry intervals, reducing leaching and improving nutrient use efficiency (Haque et al. 2022b). In CF, continuous saturation may reduce biochar's adsorption efficiency, especially in sandy soils where drainage is rapid.

The amylose and protein content are crucial for nutritional and cooking quality (Ahmed et al. 2020; Iqbal et al. 2019; Yuan et al. 2014). In this study, while slight variations in amylose content were observed across treatments, no statistically significant differences were detected among them ($p > 0.05$), as shown in Figure 4-2. This suggests that biochar application, even at higher rates combined with chemical fertilizers, did not markedly influence amylose synthesis. Nonetheless, the trend aligns with findings from Chen et al. (2023), who reported minor reductions in amylose under similar conditions. This may be due to biochar's influence on soil pH and nutrient availability, which can affect starch biosynthesis pathways. Although biochar is known to improve soil structure and water retention, its potential influence on nutrient uptake related to amylose biosynthesis remains inconclusive and warrants further investigation (Ullah et al. 2024). On the other hand, T3 in both clay and sandy loam led to the highest total protein levels (Figure 4-1b and Fig. 2). AWD and CF methods had similar effects on rice protein, and both irrigation methods showed significant benefits when combined with biochar. The results of this study were similar to those of Fahad et al. (2016) and Novak et al. (2019), who observed that biochar improved yield and quality through higher amino acid and N availability. Additionally, biochar-enhanced nitrogen metabolism, including nitrate reductase, glutamine synthetase, and glutamine 2-oxoglutarate aminotransferase activities, further contributed to efficient nitrogen utilization and improved grain protein content (Ali et al. 2020b).

The combined application of biochar and chemical fertilizer enhanced nutrient availability and uptake, resulting in higher P content in leaves (Fig. 1i and Fig. 2). These findings align with the results of Ali et al. (2020b) which also highlighted biochar's role in improving soil fertility and nutrient retention. The higher nutrient content under AWD may be due to reduced nutrient leaching compared to CF, as supported by Song et al. (2021). Shen et al. (2016) revealed that P uptake by plants notably improved by 76% after applying biochar to the soil. Biochar improves P utilization efficiency and reduces P loss, enhancing root growth and crop production (Fei et al. 2019; Olmo et al. 2016). Additionally, biochar stimulates chlorophyll synthesis, increasing photochemical efficiency, quantum yield, and electron transport rate, leading to improved photosynthesis and higher rice productivity (Ali et al. 2020b). However, this study indicated short-term benefits for rice yield and nutrient retention, while past research shows that ongoing biochar use improves nitrogen uptake, yield, water-use efficiency, and grain size over time (Fahad et al. 2016; Huang et al. 2018). Therefore, further long-term field studies are needed to fully understand the sustained impact of biochar on soil health and crop productivity.

In this study, chemical fertilizer combined with biochar 6 t ha^{-1} (i.e., T3) significantly reduced NO_3^- and NH_4^+ loss in both soil types and irrigation methods. The starting levels of NO_3^- and NH_4^+ were about the same in S1 and S2 (see Supplementary Table S1), but more of them were lost through leaching in S2 (Figure 4-3), showing that nitrogen breaks down more quickly in sandy soil. According to Liu et al. (2017), using biochar likely helps soil hold onto nitrogen better because it improves the soil's ability to hold water and increases the cation exchange capacity, along with helping microbes keep nitrogen in the soil (Jiménez et al. 2023). This explains why clay soils (59.62% clay) show less NO_3^- and NH_4^+ loss than sandy loam (8.68% clay). Biochar's SSA and CEC help retain nitrogen in clay soils by adsorbing ammonium and reducing mobility. In sandy loam, its porous structure slows water movement and nutrient loss, improving retention (Torchia et al. 2025). In terms of irrigation practices, CF irrigation resulted in higher nutrient loss compared to AWD. In CF, the soil stays saturated, increasing N leaching into groundwater. In AWD, soil alternates between wet and dry periods, better retaining nutrients and reducing N loss. Clay soil showed superior nutrient retention compared to sandy loam, and AWD was more effective in retaining nutrients and reducing N loss than CF (Phwe and Chidthaisong 2019).

Interestingly, chemical fertilizer combined with biochar 6 t ha^{-1} (i.e., T3) exhibited the lowest PO_4^{3-} loss in both soil types and irrigation methods. Specifically, adding biochar 6 t ha^{-1} worked particularly well in S2 under AWD, significantly reducing leaching compared to biochar 4 t ha^{-1} and chemical fertilizer alone. This higher rate of biochar application enhances the soil's ability to retain P, preventing it from leaching into the groundwater (Yang et al. 2022). Therefore, a higher biochar application rate, T3, proved to be more effective in reducing PO_4^{3-} loss compared to other treatments. Biochar is an efficient PO_4^{3-} adsorbent in soil (Eduah et al. 2019; Fei et al. 2019; Zhang et al. 2016) and can reduce PO_4^{3-} loss via P adsorption (Dari et al. 2016). Its ability to exchange anions also helps reduce P loss by capturing insoluble PO_4^{3-} (Chintala et al. 2014). However, Pratiwi et al. (2016) found that biochar's ability to take in PO_4^{3-} content was sometimes not very effective, such as at a rate of 4% w w^{-1} in loamy soil, and it struggled to dissolve some initial PO_4^{3-} contents below 60 mg L^{-1}.

While these findings underscore the effectiveness of biochar, particularly at 6 t ha^{-1} in reducing nutrient loss and enhancing rice yield, they need to be considered within the context of the study's design. This study was conducted at the column scale under controlled conditions, which allowed for precise monitoring of soil and water dynamics. However, this setup may not fully capture the complexity of field-scale interactions. Therefore, future field-scale research is essential to validate these findings under real-world conditions and assess their practical relevance for Cambodian rice production systems.

6. Conclusion

Incorporating biochar with chemical fertilizer could significantly enhance nutrient uptake and improve rice yield and quality while reducing nitrogen and phosphorus loss via leaching. Specifically, T3 (chemical fertilizer combined with biochar 6 t ha^{-1}) increased rice yield by 40% compared to T1 (chemical fertilizer only) for clay soil under Alternate Wetting and Drying (AWD), and by 35% and 37% for sandy loam under AWD and Continuous Flooding (CF), respectively. Increasing the biochar rate from 4 to 6 t ha^{-1} further enhances these benefits, demonstrating the importance of optimizing biochar application rates. Notably, biochar not only improves yield but also enhances the protein content in rice, accordingly contributing to better rice quality and health benefits. When combined with the AWD irrigation method, biochar proves advantageous for both clay soil and sandy loam. This combination helps retain essential nutrients and minimizes nutrient leaching into groundwater, contributing to more efficient and sustainable agricultural practices. Although the benefits of biochar in reducing nutrient loss and enhancing soil fertility are evident, it is important to limit its use to a specific amount. Further research should focus on long-term field experiments to validate these findings. Additionally, studies should consider the agricultural cost and economic benefits to assess the economic viability of biochar use under Cambodian farming conditions.

Chapter 5

General Discussion

1. Soil column: choice of selection and impact

1.1. Justification of soil column experiments

Soil column experiments are widely recognized as a robust method for studying nutrient dynamics, leaching behavior, and plant responses under controlled conditions (Ikoyi and Schmalenberger 2021b). Unlike field trials, which are subject to environmental variability, soil columns allow researchers to isolate specific factors influencing nutrient movement and crop growth. This precision is particularly important in rice systems, where nutrient losses through leaching are a major constraint to yield and input efficiency. By simulating irrigation regimes such as continuous flooding (CF) and alternate wetting and drying (AWD), soil column experiments provide mechanistic insights into nutrient retention and water dynamics that can inform practical recommendations for sustainable rice farming (Lewis and Sjöstrom 2010).

In the context of rice cultivation, where nutrient losses through leaching are a significant concern, soil column experiments offer insights into how different soil types interact with fertilizers and biochar (Kong et al. 2020a). By mimicking real-world irrigation conditions, continuous flooding (CF) and alternative wetting and drying (AWD), these experiments provide essential data on nutrient retention, which can inform practical recommendations for sustainable rice farming.

1.2. Disturbed and undisturbed soil column

This study employed both disturbed and undisturbed soil columns to evaluate nutrient leaching and biochar interactions. Disturbed columns, reconstructed from homogenized soil, facilitate uniform amendment distribution and treatment replication. However, they disrupt natural pore structure, potentially altering water flow and nutrient retention. In contrast, undisturbed columns preserve the original layering, compaction, and pore continuity, offering a more realistic simulation of field conditions (Phuong et al. 2020).

These findings showed no statistically significant differences in nutrient retention between disturbed and undisturbed columns. However, undisturbed columns demonstrated more consistent water flow and clearer representation of soil texture effects. This observation aligns with Ikoyi and Schmalenberger. (2021), who emphasized that undisturbed cores better capture hydraulic conductivity and pore continuity. Similarly, Phuong et al. (2020) found that undisturbed samples provide more reliable insights into leaching dynamics under AWD. Conversely, Lewis and Sjöstrom, (2010) argued that disturbed columns, while less representative, offer greater reproducibility. Taken together, these comparisons highlight a trade-off: disturbed columns are useful for controlled replication, but undisturbed columns are superior for simulating real-world Cambodian rice systems.

Based on these insights, the second-year experiment relied exclusively on undisturbed columns. This choice ensured that nutrient movement and biochar effects were studied under conditions that closely mimic farmer fields, while also reducing handling errors during sampling and transport.

1.3. Column stratification and the real context

The experimental design incorporated stratification of two key soil layers, the plowed layer and the compacted plow sole, which are characteristic of Cambodian rice fields. This stratification allowed for a nuanced assessment of nutrient retention across different textures, reinforcing the utility of soil columns for analyzing biochar interactions before scaling up to field applications. Similar approaches have been reported in tropical systems, where stratified soil columns improved understanding of nutrient leaching pathways (Zhao et al. 2019).

Nevertheless, soil column experiments remain limited in scope. They excel at controlling variables and isolating mechanisms, but cannot fully capture long-term ecosystem interactions, such as microbial community shifts, organic matter turnover, or cumulative nutrient cycling. As highlighted by Phuong et al. (2020), column studies should be complemented by field trials to validate mechanistic findings under farmer-managed conditions. This integration is particularly important in Cambodia, where diverse soil types and irrigation practices interact with biochar in complex ways.

2. Biochar and its role in soil and plant

2.1. How the nutrient losses under CF and AWD?

Nutrient losses are one of the most critical constraints in rice production systems, particularly in Southeast Asia where fertilizer use efficiency is low, and leaching contributes to persistent yield gaps (Haque et al. 2022a). This research demonstrated that rice husk biochar significantly reduced nitrogen (N) and phosphorus (P) losses under both continuous flooding (CF) and alternate wetting and drying (AWD). At a benchmark rate of 4 t ha^{-1}, total N leaching declined by 25–30% compared with CF alone, while P losses fell by 15–20%. These reductions are especially relevant in Cambodian rice systems, where farmers often apply fertilizers inefficiently and nutrient losses directly undermine productivity.

Under CF, prolonged anaerobic conditions immobilize some nutrients but also promote methane emissions and reduce phosphorus availability (Malyan et al. 2021). AWD, by contrast, introduces aerobic pulses that enhance nutrient uptake but increase the risk of nitrate (NO_3^-) and phosphate (PO_4^{3-}) leaching (Cheng et al. 2022). Biochar moderated these extremes by adsorbing ammonium and nitrate and binding soluble phosphorus, stabilizing nutrient availability during irrigation transitions. Its porous structure and surface functional groups act as both physical and chemical sinks, slowing nutrient movement through the soil profile (Mensah et al. 2025b).

Beyond adsorption, biochar significantly influences microbial dynamics. Studies in China and Vietnam have shown that biochar provides protective microhabitats for nitrifying and denitrifying bacteria, thereby altering the timing and intensity of nutrient transformations (Zhong et al. 2025). This microbial buffering effect helps synchronize nutrient pulses with crop demand, reducing overall losses during AWD drainage events (Omokaro et al. 2025b). In tropical soils, the high cation exchange capacity (CEC) of biochar further enhances the retention of ammonium and phosphate, complementing its physical adsorption properties to maintain long-term fertility (Antonangelo et al. 2024).

In China, Zhang et al. (2022) demonstrated that biochar application significantly enhanced nutrient retention and nitrogen use efficiency in flooded rice systems by reducing ammonia volatilization and nitrogen leaching. Similarly, Haque et al. (2021) shared that combining AWD with biochar not only buffered against nutrient losses during the "drying" phases but also improved overall rice productivity and water-use efficiency. In temperate regions, Ikoyi and Schmalenberger (2021) emphasized that biochar's role in nutrient cycling is heavily influenced by soil moisture regimes, noting its capacity to maintain microbial activity and nutrient availability even under fluctuating water levels.

Beyond East Asia, trials in India using higher application rates (10–15 t ha^{-1}) have shown dramatic reductions in nitrate leaching, although, as noted, these rates often exceed the economic reach of smallholder farmers (Biederman and Harpole 2013b; Haque et al. 2021). Studies in Africa and other tropical regions (Joseph et al., 2010) highlight biochar's critical role in coarse, highly weathered soils where leaching is most severe; in these environments, biochar's high cation exchange capacity (CEC) provides a vital "safety net" for ammonium and phosphate (Hossain et al. 2020; Sekoai and Habimana 2025). While temperate systems often prioritize biochar for water retention, in tropical systems like Cambodia, the primary advantage remains its ability to stabilize nutrient pulses and mitigate the inherent risks of AWD-induced leaching.

2.2. How does the biochar work in specific soil types?

The effectiveness of rice husk biochar is heavily mediated by soil physical properties and the specific dynamics of the soil profile. In coarse-textured sandy loams, biochar serves as a critical intervention against the rapid leaching of mobile ions (Bekchanova et al. 2024). Findings from the second-year experiment demonstrated that biochar could reduce nitrate and ammonium losses by up to 40% under Alternate Wetting and Drying (AWD) conditions, leading to substantial yield increases. This aligns with research in the Mekong Delta, where Phuong et al., (2020) observed that biochar's high internal porosity and surface area provide a "safety net" for nutrients in sandy soils that otherwise lack the surface charge to retain them. In contrast, in heavy clay soils, while biochar still mitigates nutrient leaching, the yield response is often more modest. This phenomenon is supported by Kong et al. (2020), who suggest that the high native Cation Exchange Capacity (CEC) and micro-porosity of clay minerals already provide significant nutrient buffering, thereby partially masking the supplemental benefits of biochar.

Beyond surface interactions, the spatial distribution of nutrients across the soil profile is a key determinant of fertilizer use efficiency. The first-year research using high-resolution soil column analysis revealed that biochar acts as a vertical interceptor, significantly altering how nutrients migrate through different soil layers. By increasing the retention of NH_4^+ and PO_4^{3-} in the upper root-zone, biochar prevents the "wash-out" of fertilizers into deeper, inaccessible sub-soil layers. This vertical stabilization is particularly vital in tropical environments where heavy irrigation or monsoonal rainfall can rapidly transport soluble nutrients below the rhizosphere (Joseph et al. 2010). The ability of biochar to maintain high nutrient concentrations in the top-soil, even under downward water flux, ensures a more consistent supply for rice plants during critical growth stages, a mechanism also highlighted by Ikoyi and

Schmalenberger (2021) in their study of nutrient dynamics under variable moisture regimes.

2.3. Biochar application rate

Determining an optimal application rate is essential for balancing agronomic gains with socio-economic feasibility for smallholder farmers. A rate of 4-6 t ha^{-1} has emerged as a robust benchmark, providing measurable improvements in nutrient distribution and yield without requiring the massive capital investment associated with higher rates. This benchmark is supported by Haque et al. (2021), who noted that moderate biochar amendments are sufficient to improve soil physical properties and nutrient retention in paddy systems. While larger-scale trials in China and India often utilize rates exceeding 10–20 t ha^{-1} to achieve maximum chemical shifts(Biederman and Harpole 2013a), these levels are frequently cited as economically impractical for the Southeast Asian context. The 4-6 t ha^{-1} rate effectively balances the need for a "buffer" against nutrient leaching, especially in the nutrient-poor soils of Cambodia, while remaining a realistic target for farmers utilizing local rice husk feedstock.

2.4. Synergy: Can we use biochar as a buffer for AWD risks?

While AWD is widely promoted as a water-saving irrigation strategy, several studies have noted that it can sometimes reduce yield compared with continuous flooding, particularly when nutrient losses are not well managed (Gao et al. 2024; Vicente et al. 2025). This experiment confirms this risk: under AWD alone, nutrient pulses coincided with drainage events, leading to greater nitrate and phosphate leaching. However, when AWD was combined with rice husk biochar, yield reductions were not only prevented but reversed. Biochar’s nutrient-retention capacity stabilized nitrogen and phosphorus availability during AWD cycles, ensuring that nutrient pulses aligned with root growth stages rather than being lost to leaching.

This synergy is critical for Cambodian rice systems. Farmers face increasing pressure to adopt AWD due to water scarcity and climate variability, yet concerns about yield penalties limit adoption. By demonstrating that AWD + biochar can deliver both water savings (15–20%) and yield gains (10–15%), this study provides evidence that biochar can act as a “buffer” against AWD’s agronomic risks. This dual benefit underscores biochar’s role as a complementary technology that makes AWD more viable for smallholders.

International literature supports this interpretation. Chen et al. (2025) reported that biochar enhanced nutrient retention under flooded conditions, while Ikoyi and Schmalenberger (2021) emphasized biochar's stabilizing role under variable moisture regimes. Our findings extend these insights by showing that biochar not only stabilizes nutrient cycling but also protects yield under AWD, a result particularly relevant for drought-prone regions in Southeast Asia.

2.5. Environmental implications

Beyond nutrient retention, irrigation strategy intersects with environmental trade-offs. Continuous flooding (CF) generally suppresses nitrate leaching due to prolonged soil saturation, but this anaerobic environment promotes methane emissions. In contrast, alternate wetting and drying (AWD) substantially reduces methane fluxes, though the intermittent aerobic phases can trigger short-term nitrous oxide (N_2O) pulses if nutrient management is not optimized (Chen et al. 2025b; Gao et al. 2024). Gao et al. (2024) highlight biochar's potential to reduce greenhouse gas emissions when integrated with AWD, reinforcing the global relevance of our findings.

From a socio-economic perspective, AWD adoption requires tighter water control, field-level monitoring, and additional labor, which can be challenging for smallholders (AASET 2025; Evangelista et al. 2026). CF remains popular for its simplicity despite higher water use and greenhouse gas emissions. This result suggest that combining AWD with biochar offers a pathway to reconcile productivity, resource efficiency, and environmental sustainability. However, adoption hinges on farmer access to training, reliable water infrastructure, and affordable biochar production.

Taken together, these findings demonstrate that irrigation management strongly mediates biochar's effectiveness. Under CF, nutrient retention improved, but yield gains were modest, whereas AWD combined with biochar produced both reduced leaching and enhanced yield. This dual benefit underscores the importance of integrating biochar with water-saving irrigation practices, a strategy that resonates with global calls for climate-smart agriculture while directly addressing Cambodian challenges of nutrient loss, water scarcity, and yield gaps.

2.6. Biochar effects on yield and grain quality

2.6.1. How the yield response to biochar application?

This research demonstrated that rice husk biochar improved rice yields under both continuous flooding (CF) and alternate wetting and drying (AWD), though the magnitude of improvement differed. Yield increases of 10–15% were observed under AWD, while CF showed more modest gains. These results confirm biochar's role in improving nutrient availability and synchronizing nutrient pulses with plant demand .

International literature reinforces this pattern. Zhao et al. (2021) reported that biochar combined with AWD enhanced rice productivity in Chinese soils, while Chen et al. (2025) emphasized biochar's stabilizing effect on nutrient retention under flooded conditions. Sriphirom et al. (2021) demonstrated that biochar application in rice cultivation not only reduced methane emissions but also enhanced grain yield and improved soil fertility in Thailand. Also, Phuong et al. (2020) found that AWD systems in Vietnam benefited from biochar's ability to reduce nitrate leaching, leading to yield improvements comparable to those of this research. Joseph et al. (2021) further explained that biochar improves nitrogen use efficiency by enhancing root–soil contact and microbial activity in the rhizosphere. These findings situate the Cambodian results within a broader global context, confirming that biochar consistently enhances yield across diverse rice systems.

Mechanistically, the superior yield response under AWD can be attributed to biochar's capacity to act as a chemical and physical reservoir. During the aerobic "drying" phases of AWD, nitrification often converts ammonium to highly mobile nitrate; without biochar, these nutrients are frequently lost to leaching upon re-flooding (Chen et al. 2026). Biochar mitigates this by adsorbing ammonium and nitrate within its porous structure and surface functional groups, ensuring they remain in the rhizosphere for uptake during active growth stages. Furthermore, Liu et al. (2021) highlight that biochar improves "root-soil contact," where the biochar particles act as nutrient-dense microhabitats that encourage root proliferation and microbial activity. This enhanced interception of nutrients directly translates into higher grain weight and improved nitrogen use efficiency (NUE), as noted by Alhaj Hamoud et al. (2019) in their foundational work on biochar-soil interactions.

For the Cambodian agricultural landscape, these yield responses address a critical bottleneck: the persistent yield gap caused by low fertilizer efficiency and high leaching in sandy-textured soils. By utilizing rice husk, a locally abundant and low-cost byproduct, farmers can achieve a 10–15% yield increase under water-saving

AWD regimes without radical shifts in traditional management practices (Haque et al. 2022a). While this research provides strong evidence of short-term agronomic benefits, the long-term persistence of these gains across multiple seasons remains a subject for further investigation.

2.6.2. Does biochar addition involve grain protein and quality?

Grain protein content is a critical indicator of rice quality. Our second study showed that biochar application under AWD increased grain protein by 8–12% compared with CF. This improvement reflects biochar's ability to stabilize nitrogen in plant-available forms and ensure assimilation into grain rather than loss through leaching. Recent reviews confirm that biochar enhances grain nitrogen and protein content in cereals by improving nutrient availability, water-use efficiency, and soil cation exchange capacity, thereby strengthening crop quality under climate stress (Khan et al. 2023). Although not focused on rice, meta-analysis evidence from horticultural crops further supports this, showing that biochar application significantly increased tomato yield and fruit nutritional quality, including vitamin C and soluble solids, highlighting biochar's broad capacity to improve both productivity and nutritional value across diverse cropping systems (Lei et al. 2024).

In addition to improving grain protein, several studies have suggested that biochar may positively influence rice grain quality traits including grain weight, milling quality, and nutrient composition through improvements in soil water retention and nutrient synchronization during reproductive growth stages (Ali et al. 2022; Chen et al. 2023c). Biochar's porous structure creates microhabitats that roots can colonize, enhancing root–soil contact and nutrient interception. This improved synchronization between nutrient retention and plant uptake explains why biochar not only reduces losses but also promotes assimilation into grain. Evidence from international studies (Prendergast-Miller et al. 2014), supports this mechanism, showing that biochar improves nitrogen-use efficiency through stronger root–soil interactions and stimulation of microbial activity in the rhizosphere.

However, the second study showed that biochar application under all conditions significantly alters amylose content, in contrast to the clear increases observed for grain protein. This outcome suggests that starch biosynthesis pathways are less responsive to soil nutrient stabilization than nitrogen assimilation. Similar results were reported by Chen et al. (2023), who found only minor changes in amylose under biochar treatments. The limited response of amylose is likely due to its strong genetic regulation, with varietal traits exerting greater control than soil amendments.

Consequently, while biochar enhances yield and protein quality, amylose content, and thus cooking quality, remains largely cultivar-dependent. For Cambodian rice, this distinction underscores the need to combine biochar management with varietal selection and breeding programs to achieve both nutritional enrichment and premium market positioning.

3. Integrating fertilizer practices

3.1. Insights from the farmer survey: the knowledge-practice gap

Our survey of 150 rice farmers in Santuk district revealed that fertilizer use is widespread but often not consistent. Maximum reported inputs reached 133 kg N ha^{-1}, 46 kg P_2O_5 ha^{-1}, and 30 kg K_2O ha^{-1}, yet 95% of farmers were unaware of nutrient leaching as a constraint (see 3.3). This lack of awareness highlights a critical knowledge gap: farmers apply fertilizers without recognizing the risk of nutrient losses, which contributes to yield gaps and environmental degradation. The timing of application was also inconsistent, with some farmers applying basal fertilizer at transplanting and others delaying until tillering. These practices confirm that nutrient management challenges in Cambodia are not only technical but also socio-economic and knowledge-based.

In Cambodian rice cultivation systems, fertilizer application is commonly centered on nitrogen-based fertilizers, particularly urea, due to their relatively rapid effect on crop growth and visible impact on leaf development. Farmers frequently apply fertilizers in two or three split applications during the growing season, typically at transplanting or direct seeding, active tillering, and occasionally during panicle initiation. However, application timing and dosage are often determined by farmer experience, financial capacity, weather conditions, and fertilizer availability rather than soil testing or site-specific nutrient recommendations. As a result, nutrient applications may not coincide with crop nutrient demand, increasing the potential for nutrient losses through leaching, runoff, and volatilization, especially under heavy rainfall and irrigated conditions common in Cambodian rice production systems.

3.2. Biochar × fertilizer interactions

The experiments demonstrated that rice husk biochar interacts positively with farmer-applied fertilizer regimes. When combined with chemical fertilizers, biochar reduced nitrogen and phosphorus leaching by 20–30%, effectively stabilizing nutrients at the rates farmers already use. This stabilization translated into yield gains of 10–15% under AWD and modest improvements under CF. Importantly, biochar improved nitrogen retention during critical growth stages, ensuring that fertilizer inputs were more efficiently converted into grain protein. These findings suggest that biochar can enhance the efficiency of existing fertilizer practices rather than requiring farmers to adopt entirely new regimes.

International literature supports this synergy. Joseph et al. (2010) reported that biochar improves nutrient use efficiency by increasing root–soil contact, while Zhao et al. (2019) highlighted biochar's role in synchronizing nutrient pulses with crop demand. Our results extend these insights to Cambodian soils, showing that biochar can buffer against the inefficiencies of farmer fertilizer practices.

3.3. Updating the evidence base

By integrating farmer survey data with soil column experiments, this research provides a much-needed update to the Cambodian fertilizer evidence base. Earlier regional studies, such as Theng et al. (2014), primarily emphasized direct yield responses to NPK inputs but often overlooked the underlying mechanisms of nutrient transport or the resulting grain quality. Our findings demonstrate that biochar addresses a "triple bottom line": it simultaneously reduces nutrient losses, improves yield, and enhances grain protein under real-world fertilizer regimes.

Furthermore, the economic implications of this synergy are profound. In an environment where fertilizer prices are volatile and represent a significant portion of production costs, improving Nutrient Use Efficiency (NUE) allows farmers to potentially reduce their total chemical inputs without sacrificing yield ((Phuong et al. 2020)). This is particularly relevant for the nutrient-poor, sandy soils of Cambodia where leaching is most severe. By promoting biochar as a low-cost, locally sourced complement to chemical fertilizers, extension programs can offer a pathway toward "sustainable intensification" that balances agricultural productivity with long-term environmental stewardship and farmer livelihoods.

Chapter 6

Conclusion and Perspectives

1. Conclusion

The integration of rice husk biochar into Cambodian rice production systems offers a transformative mechanism for mitigating nutrient losses and enhancing crop productivity, particularly when synchronized with water-saving irrigation strategies. This research indicates that adding biochar at the rate of 4 to 6 ha^{-1} significantly improves the rice performance in both soil and irrigation methods. These improvements are fundamentally driven by biochar's capacity to stabilize nitrogen species within the root zone, effectively reducing leaching by 20–30%. Beyond the immediate agronomic benefits, this reduction in nutrient mobility serves a critical environmental function by limiting the infiltration of nitrates and phosphates into the water table, thereby protecting groundwater quality from agricultural runoff, a vital consideration for the long-term ecological health of Cambodian watersheds.

Soil texture emerged as a primary determinant of biochar's efficacy throughout both studies. In the coarser-textured sandy loams, biochar acts as a vital physical and chemical sink that prevents the rapid downward flux of nutrients common in these high-macroporosity soils. In contrast, while clay soils also benefit from nutrient stabilization and microbial buffering, the yield response is typically more modest due to the inherent nutrient-holding capacity of clay minerals, which can partially mask the supplemental advantages of biochar. Furthermore, the two studies revealed a clear evolution in phosphorus dynamics; while the initial soil column study showed limited impact on phosphorus retention at lower rates, the subsequent experiment demonstrated that a 6 t ha^{-1} application significantly reduced phosphorus loss, particularly in sandy loams under AWD. This suggests that a higher application threshold is required to provide sufficient surface functional groups to effectively bind phosphorus under the fluctuating redox conditions of water-saving regimes.

Beyond agronomic quantity, biochar application significantly influences the nutritional and cooking quality of the rice grain. The observed 8–12% increase in grain protein content indicates superior nitrogen assimilation, which holds substantial value for food security in rice-dependent communities. However, the concurrent reduction in amylose levels suggests that while biochar enhances nutritional density, it may also alter starch composition and cooking properties, a factor that must be managed to meet specific consumer preferences.

Ultimately, biochar serves as a critical "buffer" that makes AWD irrigation more viable for smallholders by preventing the nutrient flushing and yield penalties often associated with drying-reflooding cycles. By reconciling water conservation with nutrient preservation, biochar offers a pathway toward climate-smart agriculture that safeguards both surface productivity and groundwater integrity.

2. Perspectives

2.1. Feestock selection: Is rice husk the only feedstock in Cambodia?

2.1.1 Availability of agricultural biomass feedstocks

Cambodia possesses a wide variety of agricultural residues with potential for biochar production. In addition to rice husk, biomass resources such as rice straw, cassava stems, corn stover, mango seeds, cashew nut shells, and cashew pruning residues (MAFF 2024) are increasingly recognized as promising feedstocks due to their abundance and lignocellulosic composition. These biomass materials can be converted into biochar with varying physicochemical properties depending on feedstock type and pyrolysis conditions.

According to the studies of Theng et al. (2021), rice straw and corn stover are among the most abundant field residues and are frequently burned after harvest to facilitate land preparation for the following cropping season. Cassava stems are commonly available in cassava-producing provinces and provide a relatively woody biomass source with high carbon content. Cashew nut shells and pruning residues have also gained attention because of their high calorific value and potential for producing carbon-rich biochar. In addition, mango seed waste generated from processing activities represents another emerging biomass resource with valorization potential.

2.1.2 Why was rice husk selected for this study?

Although multiple biomass resources are available in Cambodia, rice husk was selected as the primary feedstock for this study for several practical, environmental, and agronomic reasons. First, rice husk is continuously generated in large quantities as a byproduct of rice milling, representing approximately 20–22% of paddy weight (Morimoto et al. 2023). Unlike seasonal field residues, rice husk is concentrated around rice mills, which simplifies collection, transportation, and processing for biochar production.

Second, rice husk possesses unique physicochemical characteristics that are beneficial for biochar production and soil application. In particular, rice husk contains relatively high silica content (Nzereogu et al. 2023) compared to many other agricultural residues. During pyrolysis, part of this silica remains within the biochar structure, contributing to improved porosity, surface stability, and water retention properties. Silicon is also considered a beneficial element for rice cultivation because it can improve plant resistance to lodging, pests, diseases, and abiotic stresses such as drought (Yang et al. 2024b). Furthermore, rice husk biochar often exhibits high stability and persistence in soil, making it suitable for long-term carbon sequestration and nutrient retention.

Overall, rice husk is not the only potential feedstock for biochar production in Cambodia. Various agricultural residues, including rice straw, cassava stems, corn stover, mango seeds, and cashew byproducts, also possess considerable potential for biochar conversion. However, due to its continuous availability, concentration around rice mills, relatively low competing uses (for small and medium rice mills), and favorable physicochemical properties, particularly its high silica content and stable porous structure, rice husk represents a practical and strategic starting point for biochar development in Cambodia before expanding to other feedstock types.

2.2. Biochar application: challenges to adoption

One of the most persistent barriers to biochar adoption in Cambodia is the widespread confusion between genuine biochar and rice-husk ash. Ash, produced by open burning, is highly alkaline, rich in mineral oxides, and contains little residual carbon. These properties lead to rapid nutrient leaching, soil pH spikes, and poor long-term fertility outcomes. In contrast, true biochar is produced under low-oxygen pyrolysis (400–600 °C), yielding a material with over 50% stable organic carbon, a porous structure that adsorbs nutrients, and a cation-exchange capacity that synchronizes nutrient release with crop demand. Despite these differences, many smallholders mistake ash's powdery appearance for efficacy, undermining both agronomic outcomes and farmer trust. Addressing this challenge requires targeted education, demonstration projects, and the establishment of certification standards to distinguish authentic biochar from ash-like substitutes.

High upfront costs represent another major constraint. With market prices ranging from USD 100–200 per ton, and recommended application rates of 4–6 t ha^{-1}, adoption is financially prohibitive for most smallholders. Limited access to credit and cooperative structures further compounds this challenge. In addition, poorly managed pyrolysis processes can emit greenhouse gases, while contaminated feedstocks risk introducing polycyclic aromatic hydrocarbons (PAHs) or heavy metals into soils. These risks highlight the importance of quality assurance, safe production practices, and financing mechanisms that reduce the economic burden on farmers.

Although biochar has demonstrated considerable potential for improving soil fertility and nutrient retention, its adoption among smallholder rice farmers in Cambodia may be constrained by economic factors. While this study did not directly assess farmers' willingness to pay for biochar, it is reasonable to assume that adoption would remain limited if biochar costs substantially exceed existing fertilizer expenditures under smallholder farming conditions. The most recent news by Khmer Time, Cambodian rice farmers commonly operate under tight financial constraints and prioritize inputs that provide immediate and economically visible returns. He use 250kg of fertilizer per hectare, and each 50kg bag now costs around 150,000 riels ($37.50). Therefore, reducing biochar production costs through local feedstock utilization, farmer cooperatives, decentralized production systems, or integration with carbon financing mechanisms may be necessary to improve affordability and encourage wider adoption.

2.3. Strategies for scaling sustainable biochar adoption in Cambodia

2.3.1 Education and Demonstration

Farmer misconceptions about biochar versus ash remain widespread. To address this, targeted education programs are essential. Workshops, demonstration plots, and farmer field schools can showcase the production of genuine biochar through low-oxygen pyrolysis and highlight its agronomic benefits compared to ash. Extension services should emphasize practical differences, such as biochar's porous structure and nutrient retention capacity, and provide hands-on training in small-scale kiln operation. Demonstration projects allow farmers to observe yield improvements and soil health benefits directly, building trust and confidence in biochar as a sustainable amendment.

2.3.2 Quality assurance

A lack of standardized quality control undermines farmer confidence. Certification schemes and labeling systems can ensure that biochar sold in markets meets minimum thresholds for carbon content, pH, and heavy-metal safety. Government agencies, in collaboration with cooperatives and NGOs, could establish a “Cambodian Biochar Standard” modeled on the European Biochar Certificate. Clear labeling would help farmers distinguish authentic biochar from ash-like products, reducing confusion and promoting consistent agronomic outcomes. Transparent supply chains and verified testing would also encourage private-sector investment.

2.3.3. Phased application

High upfront costs discourage adoption, but staggered application strategies offer a practical entry point. Farmers can begin with small doses (e.g., 1 t ha^{-1} annually) and gradually scale up to 4–6 t ha^{-1} as yield gains and soil improvements become evident. This phased approach aligns financial investment with agronomic returns, easing economic pressures while allowing farmers to monitor crop responses. Extension services should provide guidelines for incremental application tailored to soil type, ensuring that benefits accumulate without overwhelming farmers financially.

2.3.4. Integration with AWD

Alternate Wetting and Drying (AWD) irrigation is increasingly promoted in Cambodia for water savings, but farmers worry about yield penalties due to nutrient losses during drainage events. Integrating biochar with AWD addresses this concern. Biochar stabilizes nutrient availability during redox transitions, ensuring that pulses of nitrogen and phosphorus align with crop demand. Evidence shows that AWD combined with biochar reduces water use by ~15%, increases yields by 10–12%, and lowers methane emissions by ~20%. This synergy strengthens the case for AWD adoption, offering both environmental and productivity benefits.

2.3.5. Cooperative models

Community-scale pyrolysis systems provide a cost-effective pathway for adoption. By pooling resources, farmer cooperatives can share equipment, labor, and knowledge, reducing net costs to less than USD 25 per hectare. Cooperative models also generate valuable byproducts such as bio-oil and syngas, which can be used locally or sold to offset costs. When paired with micro-credit schemes or carbon credit revenues, these models make biochar adoption financially viable and socially inclusive. Cooperative structures further enhance farmer-to-farmer learning, accelerating diffusion of best practices.

Taken together, these strategies provide practical pathways for overcoming farmer misconceptions, reducing costs, and ensuring safe and effective biochar use in Cambodian rice systems. Yet, for adoption to be sustainable and internationally credible, Cambodia's practices must also be aligned with global biochar research and certification frameworks. This alignment is essential to ensure that local innovations contribute to broader climate and soil health goals, while meeting international standards of quality and safety.

2.4. Aligning Cambodian practices with global biochar trends

Global biochar research emphasizes feedstock selection, improved pyrolysis efficiency, greenhouse gas monitoring, and standardized field testing (Shi et al., 2024). Cambodia's approach, using rice husks, decentralized kilns, cooperative networks, and carbon finance, aligns with these global directions but differs in regulatory development.

To adapt the European Biochar Certificate locally, Cambodia should establish standards for ash-free carbon content, safe heavy-metal levels, and suitable pH ranges. A new research consortium is currently investigating biochar–soil interactions across seven agro-ecological zones, with plans to publish best-practice guidelines in the future. These efforts are critical to ensure Cambodian biochar projects meet international standards while remaining context-specific.

2.5. Carbon credit initiatives and emerging investment models

In Cambodia, innovative developers such as Midori Climate Partner, Carbonaires, and HUSK Venture are pioneering models that convert agricultural residues, including rice husks and cashew shells, into biochar. These initiatives aim not only to improve soil health and agricultural productivity but also to generate durable carbon removal credits for voluntary carbon markets. By combining technical expertise, private investment, and climate finance mechanisms, these projects support rural farming communities, promote sustainable residue management, and create additional income opportunities linked to carbon sequestration.

Biochar carbon removal (BCR) projects have gained increasing international attention because biochar enables long-term carbon storage while providing agronomic and environmental co-benefits. Unlike conventional carbon offset approaches, BCR is increasingly recognized as a durable carbon dioxide removal

(CDR) pathway due to the relative stability of biochar carbon in soil. Methodologies such as the Puro.earth Biochar Methodology and emerging international carbon standards have further strengthened investor confidence by providing frameworks for monitoring and verification.

In parallel, Alternate Wetting and Drying (AWD) irrigation has emerged as an important climate mitigation strategy for rice cultivation because of its ability to reduce methane emissions and improve water-use efficiency. Together with biochar application, AWD aligns closely with Cambodia's Nationally Determined Contribution (NDC) targets for the agricultural sector. As of 2026, pilot carbon credit initiatives involving AWD and biochar application have started to emerge in major rice-producing provinces such as Battambang, Kampong Thom, Prey Veng, and Takeo through collaborations among private developers, agricultural organizations, and climate finance partners.

AWD projects primarily target methane reduction through improved irrigation management, whereas biochar initiatives focus on carbon sequestration, residue valorization, and soil fertility enhancement. Their integration may provide synergistic benefits by reducing greenhouse gas emissions while improving nutrient retention, fertilizer use efficiency, and soil resilience in rice systems. However, adoption among smallholder farmers remains constrained by high initial costs, limited technical knowledge, weak extension support, and uncertain access to carbon markets. Scaling these initiatives will therefore require stronger policy support, farmer training, accessible financing, and better integration between agricultural development and climate finance systems.

2.6. Stakeholder roles in enhancing biochar adoption

Biochar application in Cambodia remains at an early stage; strengthening stakeholder collaboration is essential to build market confidence, promote awareness, and ensure sustainable scaling. The key actors and their roles include:

- Farmers & Cooperatives: End-users, aggregators of demand, and co-investors in pyrolysis units.
- Producers & Distributors: Ensure consistent quality and transparency between biochar and ash.
- Government Agencies (MAFF, MoE): Establish enabling policies, subsidies, and integrate biochar into soil health programs.

- Research Institutions: Generate localized evidence, refine guidelines, monitor environmental safety.
- Private Sector & Carbon Credit Developers: Provide finance, technology transfer, and market access.
- NGOs & Development Partners: Facilitate training, awareness campaigns, and pilot demonstrations.
- Financial Institutions: Offer micro-credit and carbon-finance offsets to reduce upfront costs.

3. Suggested future research

To strengthen the case for biochar application, future research should prioritize:

- Long-term field trials across multiple agro-ecological zones to confirm yield and protein gains over successive seasons.
- Micronutrient dynamics, particularly interactions with iron (Fe) and zinc (Zn), are critical for rice nutrition and human health.
- Grain quality beyond protein, including starch composition, cooking properties, and consumer preferences, to enhance competitiveness in regional and global markets.
- Soil-type specific responses, distinguishing biochar's stabilizing role in clay soils from its productivity and resilience benefits in sandy soils under AWD.
- Integrated monitoring frameworks for greenhouse gas emissions, nutrient cycling, and water use efficiency, ensuring that biochar adoption contributes to climate-smart agriculture.
- Socio-economic studies on biochar adoption for soil application

4. Contribution of research

4.1. What to do with the local community?

This research contributes not only to the scientific community, through the publication of peer-reviewed articles and methodological advances in soil column experiments, but also to the farming community in Cambodia. By engaging directly with farmers in presentations and group discussions, we were able to share practical insights on biochar and nutrient leaching, raising awareness of the leaching issue, climate-smart practices such as AWD, and site-specific soil management. In this small contribution, the project bridges academic knowledge with local realities, ensuring that its impact is both scholarly and socially meaningful.

Figure 6-1 : Research contribution to the local community

4.2. Potential application beyond Cambodia

Although this study was conducted under Cambodian rice production systems and soil conditions, its findings may also have relevance to other tropical and subtropical rice-growing regions facing similar challenges related to low soil fertility, nutrient leaching, declining soil organic matter, and increasing climate pressures. Many rice cultivation areas across Southeast Asia, including parts of Vietnam, Thailand, Laos, Myanmar, and Indonesia, share comparable environmental conditions characterized by highly weathered soils, seasonal monsoonal rainfall, and intensive rice-based farming systems. In particular, sandy or low-carbon soils vulnerable to nutrient losses are widely distributed throughout the region.

The use of rice husk biochar may therefore provide broader applicability because rice husk is a common agricultural byproduct generated throughout major rice-producing countries. Likewise, the integration of biochar application with Alternate Wetting and Drying (AWD) irrigation may offer transferable benefits for improving nutrient retention, fertilizer use efficiency, soil resilience, and greenhouse gas mitigation under water-saving rice production systems. These findings are especially relevant as many countries increasingly promote climate-smart agriculture and low-carbon rice production strategies under their NDC commitments.

However, the magnitude of biochar effects may vary depending on local soil properties, climate conditions, rice varieties, feedstock types, and management practices. Therefore, while the present study provides important evidence for the potential of rice husk biochar in tropical rice systems, further validation under different agroecological conditions is necessary before broader regional generalization can be made.

5. Challenges and lessons learned

This project faced several challenges that shaped both the research process and the lessons learned. First, the work began during the COVID-19 pandemic, which made farmer interviews and field engagement extremely difficult. Lockdowns and restrictions limited direct contact, and prior to the first successful experiment, rice crops failed due to rat and insect damage when monitoring was disrupted. Second, soil column sampling proved to be highly labor-intensive, requiring significant effort to collect, prepare, and maintain samples. Finally, after the columns were carefully designed and placed under shelter, unexpected breakage destroyed part of the setup, forcing us to repeat the sampling process. These setbacks underscored the importance of resilience, careful planning, and adaptability in experimental research. The lessons learned include the need for contingency strategies in fieldwork, stronger protection of experimental setups, and patience in overcoming unforeseen obstacles. Despite these difficulties, each challenge provided valuable experience that strengthened the rigor and credibility of the final outcomes.

Figure 6-2 : Challenges encountered during the research activity

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Annex

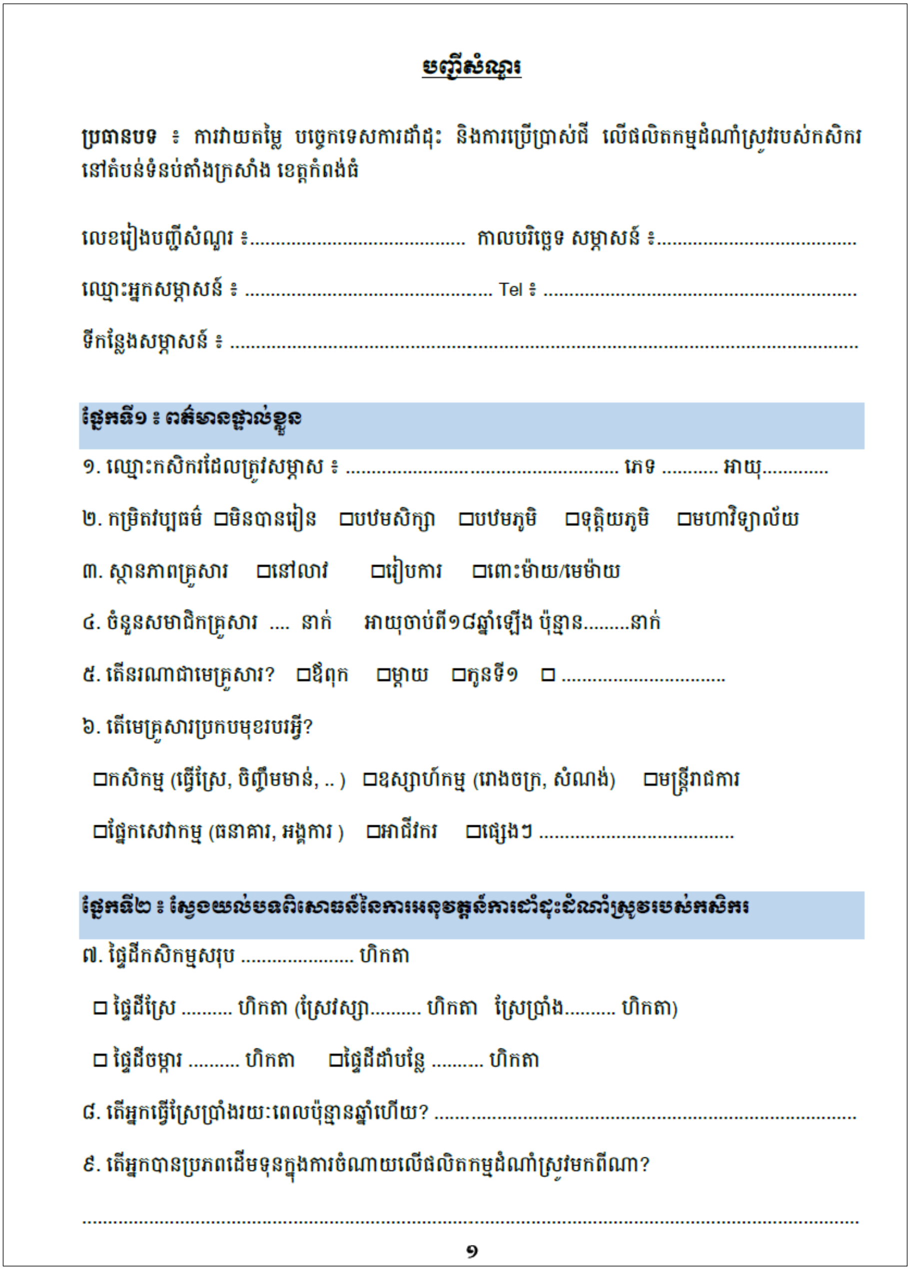
Annex 1: Overview of the group classification, details of each phase, and the estimated percentage of Cambodia's total rice area represented by each group.

Overview of group concept and phase explanation	Percentage of rice cultivation land
Group 0 - Prey Khmer This soil is found on ancient alluvial terraces or colluvial-alluvial plains, featuring a sandy profile that extends more than 50 cm deep. There are two phases: the fine sandy phase, where the sand is mainly fine (less than 0.5 mm), and the coarse sandy phase, where the sand is primarily coarse (greater than 0.5 mm).	10 - 12%
Group 1 - Prateah Lang This soil also exists on old alluvial terraces or colluvial-alluvial plains, characterized by a sandy topsoil that is less than 40 cm thick, resting above a subsoil of loamy or clayey texture. The shallow phase indicates a topsoil depth of 20 cm or less, with clayey subsoil or the presence of a very hard layer, like a plow pan or a compacted iron pan, within the top 20 cm. The clayey subsoil phase has a topsoil depth of at least 20 cm without a very hard layer in the top 20 cm, and the subsoil is clayey. The loamy subsoil phase features a loamy textured subsoil, also without a very hard layer within 20 cm of the surface.	25 - 30%
Group 2 – Labansiek This soil is found on hill or mountain slopes and features a red, clay-like surface layer with a crumb structure, underlain by a clayey subsoil. In the petroferric phase, a hard layer of ironstone several centimeters thick is located within the upper 50 cm of the soil. The nonpetroferric phase does not have this ironstone layer within the top 50 cm.	1%
Group 3 – Orung This soil develops on old alluvial terraces, showcasing a topsoil that has a loamy to clayey texture and is less than 40 cm deep, sitting on a sandy sublayer that exceeds 10 cm in thickness. There are no distinct phases identified for the Orung.	1 - 2%
Group 4 - Krakor Characterized by a gray to brown, though not excessively dark, loamy or clayey topsoil overlying a sandy, loamy, or clayey subsoil, this soil is typically found in active floodplain areas. In the cracking phase, when the soil dries,	15%

moderate to large cracks appear on the surface, extending deeper than 5 cm. The noncracking phase does not feature these cracks or only presents shallow surface cracks that do not exceed 5 cm in depth.	
Group 5 – Bakan Found on colluvial-alluvial plains or ancient alluvial terraces, this soil consists of a loamy or clayey topsoil that either does not crack or only shows shallow surface cracks, resting atop a mottled loamy or clayey subsoil. No distinct phases are defined within this Bakan phase.	10 - 15%
Group 6 - Kbal Po: This soil features a very dark gray to black clayey top layer, characterized by significant deep cracks that develop in the clay subsoil, typically found on active floodplains. Sandy layers may be present in the subsoil. In the thionic phase, the subsoil has a pH lower than 4.5, while in the nonthionic phase, the pH is above 4.5.	13%
Group 7 - Kein Svay: This soil type has a brown, loamy or clayey character in both its topsoil and subsoil, resulting in a slightly developed profile formed on river levees and surrounding backslopes. Specific phases for Kein Svay have not been established.	2%
Group 8 - Toul Samroung: Found on old alluvial terraces or colluvial-alluvial plains, this soil consists of a clayey or loamy topsoil that forms wide cracks deeper than 5 cm, sitting above a clayey or loamy subsoil. The topsoil appears gray or brown, but not a dark gray or black. In the brown phase, the surface soil is brown or light brown when wet, while in the gray phase, it appears gray or light gray when wet.	7 - 10%
Group 9 - Koktrap: This soil, located on old alluvial terraces, has a dark gray to black topsoil with a clayey or loamy texture, which overlays a light gray or light brown loamy or clayey subsoil. In the infertile phase, unfertilized rice yields in fields typically fall below 1,200 kg per hectare, generally around 500 to 800 kg. Rice plants in these soils often show slight to severe leaf bronzing. The fertile phase, however, results in unfertilized yields exceeding 1,200 kg per hectare, usually over 1,500 kg, with no bronzing of the leaves.	5%
Group 10 - Kompong Siem: This type of soil displays visible calcimorphic liestone or basalt stones and boulders either within its profile or on the surface. It has a black or dark gray clayey topsoil that develops deep cracks above a clayey	1-2%

subsoil. In the gravelly phase, numerous small, round black and brown ferro-manganese concretions are found throughout the profile, and gravel is noticeable in the surface soil. Conversely, the nongravelly phase lacks gravel throughout or only contains a few scattered concretions, or the gravel may only be concentrated in parts of the subsoil without being present in the surface soil.	

Annex 2: The questionnaire used for farmer interviews



បញ្ជីសំណួរ

ប្រធានបទ ៖ ការវាយតម្លៃ បច្ចេកទេសការដាំដុះ និងការប្រើប្រាស់ជី លើផលិតកម្មដំណាំស្រូវរបស់កសិករ នៅតំបន់ទំនប់តាំងក្រសាំង ខេត្តកំពង់ធំ

លេខរៀងបញ្ជីសំណួរ ៖... កាលបរិច្ឆេទ សម្ភាសន៍ ៖.......................................

ឈ្មោះអ្នកសម្ភាសន៍ ៖ .... Tel ៖ ....

ទីកន្លែងសម្ភាសន៍ ៖ ....

ផ្នែកទី១ ៖ ពត៌មានផ្ទាល់ខ្លួន

១. ឈ្មោះកសិករដែលត្រូវសម្ភាស ៖ .... ភេទ .... អាយុ............

២. កម្រិតវប្បធម៌ ☐មិនបានរៀន ☐បឋមសិក្សា ☐បឋមភូមិ ☐ទុតិ្តយភូមិ ☐មហាវិទ្យាល័យ

៣. ស្ថានភាពគ្រួសារ ☐នៅលីវ ☐រៀបការ ☐ពោះម៉ាយ/មេម៉ាយ

៤. ចំនួនសមាជិកគ្រួសារ .... នាក់ អាយុចាប់ពី១៨ឆ្នាំឡើង ប៉ុន្មាន.........នាក់

៥. តើនរណាជាមេគ្រួសារ? ☐ឪពុក ☐ម្តាយ ☐កូនទី១ ☐ ....

៦. តើមេគ្រួសារប្រកបមុខរបរអ្វី?

☐កសិកម្ម (ធ្វើស្រែ, ចិញ្ចឹមមាន់, ..) ☐ឧស្សាហ៍កម្ម (រោងចក្រ, សំណង់) ☐មន្រ្តីរាជការ

☐ផ្នែកសេវាកម្ម (ធនាគារ, អង្គការ) ☐អាជីវករ ☐ផ្សេងៗ ....

ផ្នែកទី២ ៖ ស្វែងយល់បទពិសោធន៍នៃការអនុវត្តន៍ការដាំដុះដំណាំស្រូវរបស់កសិករ

៧. ផ្ទៃដីកសិកម្មសរុប .... ហិកតា

☐ ផ្ទៃដីស្រែ .... ហិកតា (ស្រែវស្សា.......... ហិកតា ស្រែប្រាំង.......... ហិកតា)

☐ ផ្ទៃដីចម្ការ .... ហិកតា ☐ផ្ទៃដីដាំបន្លែ .... ហិកតា

៨. តើអ្នកធ្វើស្រែប្រាំងរយៈពេលប៉ុន្មានឆ្នាំហើយ? ....

៩. តើអ្នកបានប្រភពដើមទុនក្នុងការចំណាយលើផលិតកម្មដំណាំស្រូវមកពីណា?

....

១

១០. ចំនួនដងនៃការធ្វើស្រែក្នុង១ឆ្នាំ ☐១ដង ☐២ដង ☐៣ដង

១១. តើអ្នកធ្វើស្រែវស្សា ឬប្រាំង?

☐ស្រែវស្សា រយៈពេលប៉ុន្មានខែ......... ចាប់ពីខែ............... ដល់ខែ.............

☐ស្រែប្រាំង រយៈពេលប៉ុន្មានខែ......... ចាប់ពីខែ............... ដល់ខែ.............

១២. តើអ្នកប្រើប្រាស់ការភ្ជួររាស់មុនដាំដុះដែរ ឬទេ? ☐មិនភ្ជួររាស់ ☐ភ្ជួររាស់ (ភ្ជួរ......ដង និងរាស់.........ដង)

រយៈពេល ចាប់ពីខែ............... ដល់ខែ.............

១៣. ការចំណាយលើភ្ជួរ.................. រៀល/ha ១ដង និងការចំណាយលើរាស់.................. រៀល/ha ១ដង

១៤. តើអ្នកដុតជញ្ជ្រាំងមុនពេលដាំដុះស្រូវ ឬទេ? ☐ដុត ☐មិនដុត (រក្សាជាជី) ☐ច្រូតយកទៅប្រើប្រាស់

១៥. តើអ្នកប្រើប្រាស់ប្រភេទពូជស្រូវអ្វី នៅរដូវប្រាំង?

ពូជស្រូវរដូវប្រាំង............................... (ប្រភពពូជបានពី៖.......................................)

១៦. តើអ្នកដាំដុះស្រូវដោយវិធីណា?

☐ពង្រោះប្រើពូជប៉ុន្មានគីឡូ ..../ha ☐សន្ទូងប្រើពូជប៉ុន្មានគីឡូ ..../ha អាយុកាលសំណាប........ថ្ងៃ

១៧. តើអ្នកចំណាយលើពូជអស់ប៉ុន្មាន? .... រៀល/ha

១៨. តើប្រើប្រាស់វិធានការកម្ចាត់ស្មៅយ៉ាងដូចម្តេច?

☐ដោយការដកសម្អាតស្មៅ ☐ដោយប្រើប្រាស់ថ្នាំកម្ចាត់ស្មៅ ☐ដោយការដកសម្អាត និងថ្នាំកម្ចាត់ស្មៅ

១៩. តើប្រើប្រាស់ប្រភេទថ្នាំស្មៅប្រភេទអ្វីខ្លះ? ☐ថ្នាំបំបែកគ្រាប់ស្មៅ ☐ថ្នាំកក់ ☐ថ្នាំស្មៅទូទៅ

☐ ....

២០. តើអ្នកធ្វើការកម្ចាត់ស្មៅប៉ុន្មានដងក្នុង១វដ្តជីវិតស្រូវ? .... ដង

២១. តើចំណាយ .... រៀល/ha ក្នុង១ដង

២២. តើមានប្រើប្រាស់ថ្នាំការពារ ឬកម្ចាត់សត្វល្អិតលើដំណាំស្រូវរបស់អ្នក ឬទេ?

☐មិនប្រើប្រាស់ ☐ប្រើប្រាស់

២៣. តើអ្នកប្រើប្រាស់ប្រភេទថ្នាំការពារ ឬកម្ចាត់សត្វល្អិតអ្វីខ្លះ? ☐ ថ្នាំផ្សំពីធម្មជាតិ ☐ថ្នាំគីមី (Abamectin, Emamectin, Fipronil, ...) ☐ផ្សេងៗ ....

២៤. តើការប្រើប្រាស់ថ្នាំការពារ ឬកម្ចាត់សត្វល្អិត នៅពេលណា? ប៉ុន្មានដង? តើចំណាយសរុបប៉ុន្មាន/ha? និងចំណាយផ្សេងៗ? ....

....

....

២៥. ចំណាយលើពលកម្មបាញ់ថ្នាំការពារ ឬកម្ចាត់សត្វល្អិត .... រៀល/ha

២៦. តើអ្នកមានប្រើប្រាស់ថ្នាំការពារ ឬព្យាបាលជម្ងឺ លើដំណាំស្រូវរបស់អ្នកដែរ ឬទេ?

☐មិនប្រើប្រាស់ ☐ប្រើប្រាស់

២៧. តើប្រើប្រាស់ប្រភេទថ្នាំការពារ ឬព្យាបាលជម្ងឺ ដូចម្តេច? ☐ ថ្នាំផ្សំពីធម្មជាតិ ☐ថ្នាំគីមី (Mencozep, Hyzaconazole, Azoxytrobin, ...) ☐ផ្សេងៗ ....

២៨. តើការប្រើប្រាស់ថ្នាំ ការពារ ឬព្យាបាលជម្ងឺ នៅពេលណា? ប៉ុន្មានដង? តើចំណាយសរុបប៉ុន្មាន/ha? និងចំណាយផ្សេងៗ? ....

....

២៩. ចំណាយលើពលកម្មបាញ់ថ្នាំការពារ ឬព្យាបាលជម្ងឺ .... រៀល/ha

៣០. តើអ្នកបញ្ចូលទឹកស្រែដែរ ឬទេ? ☐មិនបញ្ចូល ☐បញ្ចូល

៣១. តើអ្នកប្រើប្រាស់ប្រភពទឹកបានមកពីណា? ☐ប្រឡាយទឹកតាំងក្រសាំង ☐អណ្តូង ☐ស្រះ

៣២. តើអ្នកប្រើប្រាស់វិធីសាស្ត្រអ្វីក្នុងការបញ្ចូលទឹក?

☐បង្ហូរផ្ទាល់ (ទំហំមុខកាតប្រឡាយចូលស្រែ ....) (រយៈពេលគិតជាម៉ោង .... ក្នុង១ដង)
(ចំនួនប៉ុន្មាន .... ដង/១វដ្តស្រូវ) ចំណាយសរុបក្នុងការបញ្ចូលទឹកអស់ប៉ុន្មាន .... រៀល/ha

☐ប្រើប្រាស់ម៉ាស៊ីនបូម (ទំហំមុខកាតទុយោ ....) (រយៈពេលគិតជាម៉ោង .... ក្នុង១ដង)
(ចំនួនប៉ុន្មាន .... ដង/១វដ្តស្រូវ) ចំណាយសរុបក្នុងការបញ្ចូលទឹកអស់ប៉ុន្មាន .... រៀល/ha

៣៣. តើប្រឡាយទឹកតាំងក្រសាំងធ្លាប់ ជួបបញ្ហាខ្វះទឹកដែរ ឬទេ? ☐មិនធ្លាប់ខ្វះខាតទឹក ☐ធ្លាប់ខ្វះខាតទឹក ក្នុងកម្រិតណា ....

....

៣៤. តើអ្នកមានការបារម្ភអំពីការខ្វះខាតទឹកធ្វើស្រូវដែរ ឬទេ? ប្រសិនបើជួបបញ្ហាខ្វះទឹក តើនឹងជួបប្រទះបញ្ហាអ្វីខ្លះ? ....

....

....

៣៥. តើអ្នកប្រមូលផលស្រូវដោយវិធីណា? រយៈពេលប្រមូលផលប៉ុន្មាន ....ថ្ងៃ?

☐ច្រូតដោយដៃ ☐ច្រូតដោយម៉ាស៊ីនស្វ័យប្រវត្ត ☐..

ចំណាយសរុបក្នុងការប្រមូលផលអស់ប៉ុន្មាន ....រៀល/ha

៣៦. តើអ្នកទទួលបានទិន្នផលប៉ុន្មានតោន/ha? .... តោន/ha ក្នុងឆ្នាំ២០២២

៣៧. តើអ្នកទទួលបានទិន្នផលប៉ុន្មានតោន/ha? .... តោន/ha (កាល៥ឆ្នាំមុន)

៣៨. បន្ទាប់ពីប្រមូលផលរួច តើអ្នកលក់ឱ្យទៅឈ្មួញតែម្តង ឬហាលស្តុកទុក?

☐លក់ .... តោន

☐ស្តុកទុក.............. តោន ដើម្បី..

៣៩. តើអ្នកលក់ស្រូវទទួលបានតម្លៃប៉ុន្មានក្នុង១គីឡូក្រាម? .... រៀល/kg នៃឆ្នាំ២០២២

៤០. តើអ្នកលក់ស្រូវទទួលបានតម្លៃប៉ុន្មានក្នុង១គីឡូក្រាម? .... រៀល/kg (កាល៥ឆ្នាំមុន)

៤១. តើអ្នកទទួលបានប្រាក់ចំណូលប៉ុន្មានក្នុង១វដ្តដំណាំស្រូវ? .... រៀល នៃឆ្នាំ២០២២

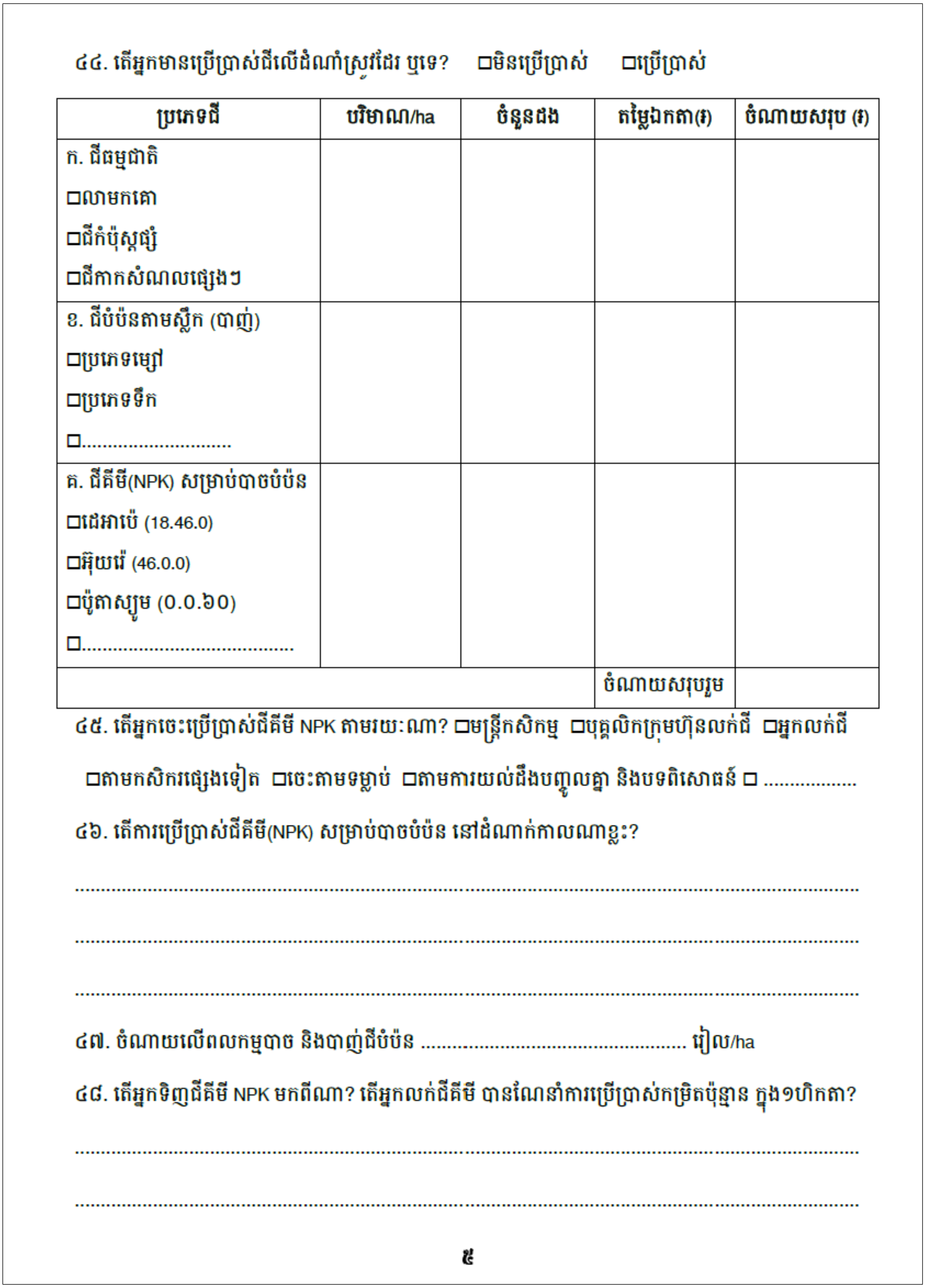
៤២. តើអ្នកទទួលបានប្រាក់ចំណូលប៉ុន្មានក្នុង១វដ្តដំណាំស្រូវ? .... រៀល (កាល៥ឆ្នាំមុន)

ផ្នែកទី៣ ៖ កំណត់ និងវាស់វែង ការយល់ដឹងលើការប្រើប្រាស់ជីរបស់កសិករ

៤៣. តើអ្នកធ្លាប់ចូលរួមវគ្គបណ្តុះបណ្តាលកសិកម្មដែរ ឬទេ? ប៉ុន្មានដង? ☐ធ្លាប់........ ដង ☐មិនធ្លាប់

បើធ្លាប់សូមបញ្ជាក់វគ្គបណ្តុះបណ្តាល៖

- វគ្គ ៖ .... រៀបចំដោយ..
- វគ្គ ៖ .... រៀបចំដោយ..
- វគ្គ ៖ .... រៀបចំដោយ..



៤៤. តើអ្នកមានប្រើប្រាស់ជីលើដំណាំស្រូវដែរ ឬទេ? ☐មិនប្រើប្រាស់ ☐ប្រើប្រាស់

ប្រភេទជី	បរិមាណ/ha	ចំនួនដង	តម្លៃឯកតា(៛)	ចំណាយសរុប (៛)
ក. ជីធម្មជាតិ ☐លាមកគោ ☐ជីកំប៉ុស្តផ្សំ ☐ជីកាកសំណលផ្សេងៗ				
ខ. ជីបំប៉នតាមស្លឹក (បាញ់) ☐ប្រភេទម្សៅ ☐ប្រភេទទឹក ☐............................				
គ. ជីគីមី(NPK) សម្រាប់បាចបំប៉ន ☐ដេអាប៉េ (18.46.0) ☐អ៊ុយរ៉េ (46.0.0) ☐ប៉ូតាស្យូម (0.0.៦0) ☐.......................................				
			ចំណាយសរុបរួម	

៤៥. តើអ្នកចេះប្រើប្រាស់ជីគីមី NPK តាមរយៈណា? ☐មន្រ្តីកសិកម្ម ☐បុគ្គលិកក្រុមហ៊ុនលក់ជី ☐អ្នកលក់ជី ☐តាមកសិករផ្សេងទៀត ☐ចេះតាមទម្លាប់ ☐តាមការយល់ដឹងបញ្ចូលគ្នា និងបទពិសោធន៍ ☐ ....

៤៦. តើការប្រើប្រាស់ជីគីមី(NPK) សម្រាប់បាចបំប៉ន នៅដំណាក់កាលណាខ្លះ?

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៤៧. ចំណាយលើពលកម្មបាច និងបាញ់ជីបំប៉ន .... រៀល/ha

៤៨. តើអ្នកទិញជីគីមី NPK មកពីណា? តើអ្នកលក់ជីគីមី បានណែនាំការប្រើប្រាស់កម្រិតប៉ុន្មាន ក្នុង១ហិកតា?

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៤៩. ការណែនាំកម្រិតប្រើប្រាស់ជីគីមីរបស់ក្រសួងកសិកម្ម ក្នុងការដាំដុះដំណាំស្រូវ

ល.រ	ក្រុមដី	ដីអ៊ុយរ៉េ	ដីដេអាប៉េ	ដីប៉ូតាស្យូម
១	ព្រៃខ្មែរ	៧៥ Kg/ha	២៥ Kg/ha	១០០ Kg/ha
២	ប្រទះឡាង	១៨៥ Kg/ha	៨៥ Kg/ha	១៣០ Kg/ha
៣	គៀនស្វាយ	១២០ Kg/ha		

តើអ្នកយល់ឃើញយ៉ាងណាចំពោះកម្រិតប្រើប្រាស់ខាងលើធៀបនឹងការអនុវត្តន៍ផ្ទាល់របស់អ្នក?

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៥០. តាមបទពិសោធន៍ និងការយល់ឃើញរបស់អ្នក តើការប្រើប្រាស់ជីគីមី (NPK) ជួយអ្វីខ្លះដល់ដំណាំស្រូវ?

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៥១. ហេតុអ្វីបានជាអ្នកប្រើប្រាស់ជីគីមី (NPK) លើដំណាំស្រូវ? ....

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៥២. តើអ្នកដឹងថាការប្រើប្រាស់ជីគីមី (NPK) មានផលប៉ះពាល់អ្វីខ្លះដល់ សុខភាព សេដ្ឋកិច្ច សង្គម? តើអ្នកដឹងតាមរយៈណា?...

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៥៣. តាមបទពិសោធន៍ តើការប្រើប្រាស់ជីគីមី (NPK) ទៅក្នុងស្រែធ្វើឱ្យមានការកើនឡើង ឬថយចុះ ជីវៈចម្រុះ ដូចជា (ខ្យង ក្ដាម ត្រី កង្កែប) ដែរ ឬទេ? ....

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៥៤. តាមបទពិសោធន៍ តើការប្រើប្រាស់ជីគីមី (NPK) ទៅក្នុងស្រែធ្វើឱ្យដីមានសុខភាពល្អ ឬអន់ជាងមុន?

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៥៥. តើអ្នកដឹងថាការប្រើប្រាស់ជីគីមី (NPK) មានផលប៉ះពាល់អ្វីខ្លះដល់ បរិស្ថាន និងផលិតកម្មដំណាំស្រូវរបស់អ្នកនៅពេលក្រោយ? ដូចជាការហូរច្រោះសារធាតុជីគីមីចូលទៅទឹកក្រោមដី ខូចគុណភាពដី ការប្រើប្រាស់ជីកើនឡើងដើម្បីរក្សាទិន្នផល ជាដើម។ ប្រសិនបើជាអាចបណ្តាលឱ្យប៉ះពាល់បែបនេះ តើអ្នកមានវិធីសាស្រ្តអ្វីដើម្បីជួយទប់ស្កាត់ ឬជួយកែប្រែការប៉ះពាល់ និងខូចខាតទាំងនេះ?

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៥៦. តើការប្រើប្រាស់ជីគីមី (NPK) លើដំណាំស្រូវរបស់អ្នក មានចំនួនតិចជាង ច្រើនជាង ឬប្រហាក់ប្រហែលគ្នាធៀបទៅនឹង៥ឆ្នាំមុន? ប្រភេទជីអ្វីខ្លះ? បរិមាណប្រើប្រាស់ជីប៉ុន្មាន?

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៥៧. នៅថ្ងៃអនាគត តើអ្នកមានគម្រោងកាត់បន្ថយការប្រើប្រាស់ជីគីមី(NPK) ឬ នៅបន្តការប្រើប្រាស់ជីគីមី (NPK) បន្តទៀត? ប្រសិនបើនៅតែបន្តប្រើប្រាស់ជីគីមី ចូរប្រាប់ពីហេតុផលដែលនៅតែបន្តប្រើប្រាស់?

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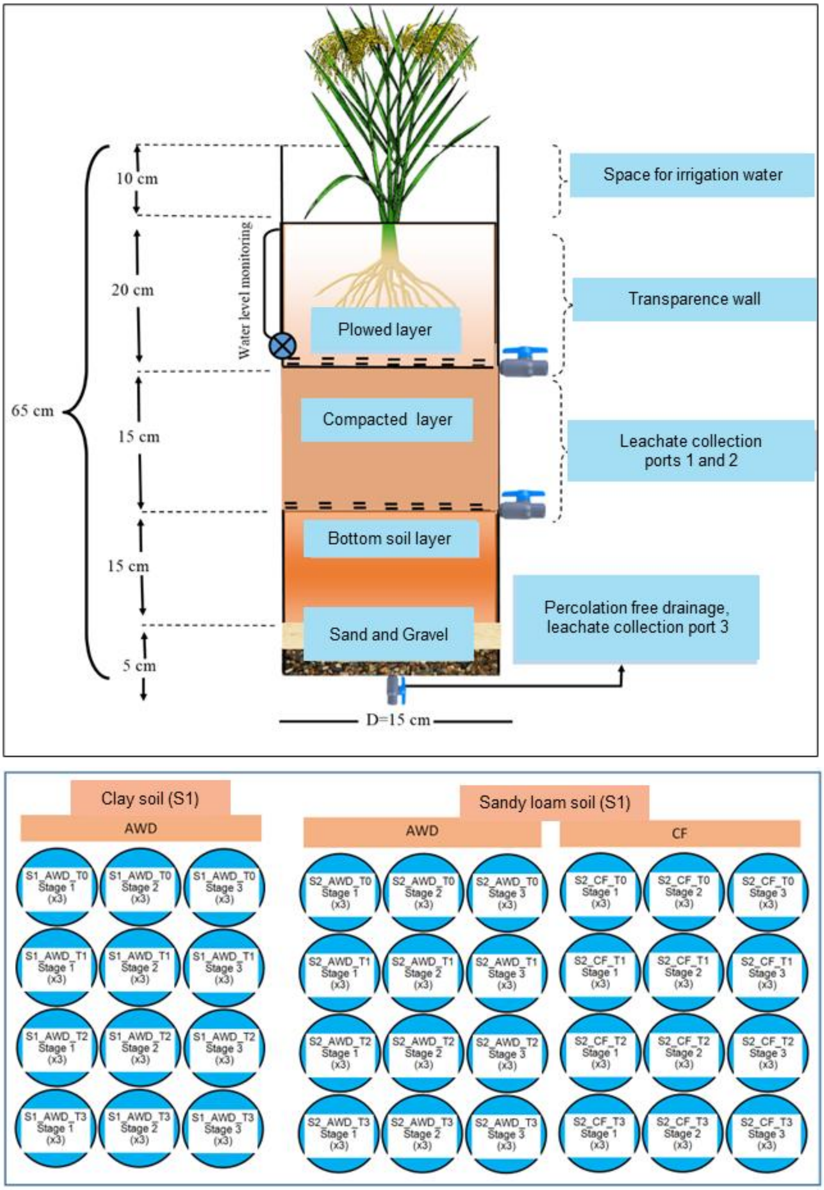
Annex 3: The activity involves breaking the soil column to collect samples of both roots and soil

Annex 4: The condition of the roots from both biochar treatment and the control group

Annex 5: Mean values (± 1 SD, standard deviation) for the rice husk biochar ($n = 3$) were randomly estimated from a 3-kg rice husk biochar, and clay soil (i.e., S1) and sandy loam (i.e., S2) of the three soil layers were estimated from the three soil profiles ($n = 9$, each). The numbers (in bold) were significantly different between the two soil types (*T-test*, $p < 0.05$).

Variables	**Biochar**	**Soils**							
		Bakan (S1) or Clay				**Prateah Lang (S2) or Sandy loam**			
		0-20 cm	**20-35 cm**	**35-50 cm**	**Mean ± SD**	**0-20 cm**	**20-35 cm**	**35-50 cm**	**Mean ± SD**
pH	8.4± 0.09	6.3	6.09	6.2	**6.2 ± 0.1**	5.10	5.1	5.7	5.3 ± 0.5
Electrical conductivity (uS cm^{-1})	57.3 ± 1.2	33.4	35.6	34.2	**34.4 ±1.4**	29.3	28.8	23.8	27.3 ± 2.8
Organic carbon (%)	54.1 ± 3.4	1.7	1.4	1.3	**1.5 ± 0.2**	1.2	0.6	0.2	0.7 ± 0.4
Soil organic matter (%)	64.8 ± 4.09	2.9	2.4	2.3	**2.5 ± 0.3**	2.1	0.9	0.4	1.2 ± 0.7
Bulk density (g cm^{-3})	-	1.4	1.6	1.5	1.5 ± 0.1	1.3	1.5	1.5	1.4 ± 0.1
Total nitrogen (g kg^{-1})	1.4 ± 0.3	1.9	2.1	0.7	**1.6 ± 0.6**	1.1	0.6	0.9	0.9 ± 0.2
Nitrate (mg kg^{-1})	85 ± 0.2	12.3	9.5	4.9	8.9 ± 3.1	9.9	7.6	3.9	7.1 ± 2.4
Ammonium (mg kg^{-1})	96.5 ± 1.3	17.7	11.0	4.3	11.0 ±5.5	14.2	8.8	4.4	9.1 ± 4.0
Available Phosphorus (mg kg^{-1})	2.9 ± 0.2	21.3	15.2	12.9	**16.5 ± 3.6**	1.6	0.9	1.1	1.3 ± 0.3
Exchangeable K (cmol kg^{-1})	1.2 ± 0.9	0.2	0.09	0.06	**0.1 ± 0.04**	0.08	0.05	0.03	0.05 ± 0.02
Cation Exchange Capacity (cmol^{+} kg^{-1})	64.2 ± 0.9	6.2	6.04	5.8	**6.0 ± 0.2**	5.6	5.9	5.2	5.6 ± 0.3
Specific surface area (m^{2} g^{-1})	102.2 ± 3.8	-	-	-	-	-	-	-	-
Sand (%)	-	23.2	19.1	16.6	19.7 ± 2.7	73.7	67.1	54.3	**65 .2 ± 8.1**
Silk (%)	-	23.6	22.7	11.5	19.2 ± 5.5	21.8	23.5	32.9	25.9 ± 5.09
Clay (%)	-	53.2	58.2	71.9	**61.1 ± 7.9**	4.5	9.4	12.8	8.9 ± 3.2

Annex 6: An undisturbed soil column (a) represents the plowed layer (20 cm), compacted layer (15 cm), and bottom soil layer (15 cm), with the first 10 cm allocated for irrigation space. Three sets of soil column samples were prepared to represent the soils used for rice in Cambodia (i.e., clay (S1) and sandy loam (S2)) under two irrigation methods.



Clay soil (S1)			Sandy loam soil (S1)					
AWD			AWD			CF		
S1_AWD_T0 Stage 1 (x3)	S1_AWD_T0 Stage 2 (x3)	S1_AWD_T0 Stage 3 (x3)	S2_AWD_T0 Stage 1 (x3)	S2_AWD_T0 Stage 2 (x3)	S2_AWD_T0 Stage 3 (x3)	S2_CF_T0 Stage 1 (x3)	S2_CF_T0 Stage 2 (x3)	S2_CF_T0 Stage 3 (x3)
S1_AWD_T1 Stage 1 (x3)	S1_AWD_T1 Stage 2 (x3)	S1_AWD_T1 Stage 3 (x3)	S2_AWD_T1 Stage 1 (x3)	S2_AWD_T1 Stage 2 (x3)	S2_AWD_T1 Stage 3 (x3)	S2_CF_T1 Stage 1 (x3)	S2_CF_T1 Stage 2 (x3)	S2_CF_T1 Stage 3 (x3)
S1_AWD_T2 Stage 1 (x3)	S1_AWD_T2 Stage 2 (x3)	S1_AWD_T2 Stage 3 (x3)	S2_AWD_T2 Stage 1 (x3)	S2_AWD_T2 Stage 2 (x3)	S2_AWD_T2 Stage 3 (x3)	S2_CF_T2 Stage 1 (x3)	S2_CF_T2 Stage 2 (x3)	S2_CF_T2 Stage 3 (x3)
S1_AWD_T3 Stage 1 (x3)	S1_AWD_T3 Stage 2 (x3)	S1_AWD_T3 Stage 3 (x3)	S2_AWD_T3 Stage 1 (x3)	S2_AWD_T3 Stage 2 (x3)	S2_AWD_T3 Stage 3 (x3)	S2_CF_T3 Stage 1 (x3)	S2_CF_T3 Stage 2 (x3)	S2_CF_T3 Stage 3 (x3)