UNIVERSITI PUTRA MALAYSIA

IMPROVING RICE YIELD (Oryza sativa L.) AND SELECTED SOIL PHYSICOCHEMICAL PROPERTIES USING ORGANIC AMENDMENTS UNDER WATER-SAVING IRRIGATION

AHMAD NUMERY ASHFAQUL HAQUE

FP 2022 32

IMPROVING RICE YIELD (*Oryza sativa* L.) AND SELECTED SOIL PHYSICOCHEMICAL PROPERTIES USING ORGANIC AMENDMENTS UNDER WATER-SAVING IRRIGATION

By

AHMAD NUMERY ASHFAQUL HAQUE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

April 2022

DEDICATION

To my beloved mother and father for their inestimable sacrifices and support entirely my life

and

To my beloved wife for her love, encouragement and my son for his sacrifices

and

To my lovely sibling

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

IMPROVING RICE YIELD (*Oryza sativa* L.) AND SELECTED SOIL PHYSICOCHEMICAL PROPERTIES USING ORGANIC AMENDMENTS UNDER WATER-SAVING IRRIGATION

By

AHMAD NUMERY ASHFAQUL HAQUE

April 2022

Chairman : Associate Professor Md Kamal Uddin, PhD
Faculty : Agriculture

Rice provides calories to more than half of the world's population, but consumes excessive water compared to other staple crops. To minimize this excess water usage alternate wetting and drying (AWD) irrigation practices are considered an efficient technique in which soil is intermittently irrigated. The addition of suitable organic amendments could help to retain soil moisture and improve physicochemical properties. In this context, four experiments were conducted to evaluate the effect of organic amendments on soil physicochemical properties for improved rice yield under water-saving irrigation. At first, an incubation study was conducted to evaluate the incorporation of five selected organic amendments—as follows: rice husk biochar (RHB), oil palm empty fruit bunch biochar (EFBB), compost, rice husk ash (RHA), and oil palm bunch ash (PBA), with a control (no amendment) on soil moisture storage and some chemical properties of soil. The soil was incubated with five amendments for 60 days and sampled at 15-day intervals. After completion of the incubation, RHB (0.46 g g^{-1}) and EFBB (0.45 g g^{-1}) exhibited greater gravimetric water content compared to the control (0.16 g g^{-1}). PBA treatment produced maximum soil pH (6.95) compared to its initial value (5.01). EFBB finally contributed to the highest total carbon (7.82%) and nitrogen (0.44%). PBA showed the highest available phosphorus (P) and exchangeable potassium (K). The second study investigated the effect of water-saving irrigation with biochar and compost on the growth, yield, water productivity of rice and physicochemical properties of soil. A glasshouse experiment was executed with two irrigation regimes namely AWD and continuous flooding (CF) and four treatments including three types of organic amendments namely RHB, EFBB, and compost applied at 4% (weight/weight), and recommended fertilizer dose (RFD). Under the AWD irrigation regimes, maximum grain was produced by RHB (241.12 g) and the lowest in the RFD (210.15 g), whereas under the same organic amendments both AWD and CF produced similar grain yields. RHB and EFBB with AWD irrigation showed better water productivity (WP) (6.30 g L^{-1} and 5.80 g L^{-1}, respectively) over control treatment under CF (3.94 g L^{-1}). Within the same irrigation soil pH, cation exchange capacity, total carbon (C), and nitrogen (N) are enhanced by biochar and compost incorporation. RHB and EFBB significantly reduced soil bulk density up to 0.88 g cm^{-3} from 1.12 g cm^{-3} and enhanced porosity up to 58.7% compared to RFD in CF irrigation. The next study was conducted to investigate the effect of biochars on rice yield, fertilizer N use efficiency, and recovery under water-saving irrigation by a ^{15}N isotopic tracer. Two types of irrigation AWD and CF, and four types of biochar treatments such as RHB with ^{15}N urea, EFBB with ^{15}N urea, ^{15}N urea alone, and control, were applied. About 4% reduced grain yield (193.89 g pot^{-1}) was achieved by the AWD regime over the CF (202.57 g pot^{-1}, whereas RHB and EFBB with ^{15}N urea significantly increased rice yield (up to 8.8%) compared to ^{15}N urea alone. RHB and EFBB with ^{15}N urea enhanced the fertilizer N recovery from ^{15}N urea (0.59 g g^{-1} and 0.61 g g^{-1}, respectively), over ^{15}N urea alone (0.49 g g^{-1}). Agronomic use efficiency and partial factor productivity of N were accelerated by RHB (32.77 g g^{-1} and 73.14 g g^{-1}, respectively) and EFBB (33.77 g g^{-1} and 74.14 g g^{-1}, respectively). The last experiment was conducted to assess the effect of biochar combined with fertilizer on physiological response, water productivity and nutrient use efficiency (NUE) of rice, and changes in biochemical properties of soil under AWD irrigation. Two types of irrigation practices such as AWD and CF and four types of fertilizer combinations namely T1: 25% RHB+75% of recommended fertilizer dose (RFD), T2: 25% EFBB+75% of RFD, T3: 100% RFD, and T0: 0% biochar and fertilizer were assigned. The AWD irrigation produced a sharply reduced grain yield (210.58 g pot^{-1}) compared to CF irrigation (218.04 g pot^{-1}), whereas the biochar combination treatments T1 and T2 produced greater yields (260.27 g pot^{-1} and 252.12 g pot^{-1}, respectively), which were up to 12.5% higher than RFD (231.27 g pot^{-1}). Within AWD, irrigation water usage by T1 and T2 (98.50 Land 102.38 L, respectively) was profoundly reduced by up to 28.8% over CF with T3 (138.25 L), with improved WP. The main effect of biochar treatment T1 and T2 also increased photosynthesis rate (21.31 and 20.950 µmol $m^{-2}s^{-1}$, respectively) compared to RFD (17.63 µmol $m^{-2}s^{-1}$), in addition to boosted agronomic efficiency of N, P and K compared to RFD. Nevertheless, T1 and T2 significantly enhanced the total carbon and nitrogen; dehydrogenase and urease enzyme activities also increased in both irrigation regimes. The results reveal that the integrated application of RHB and EFBB with the AWD regime highly reduces irrigation water and improves NUE, WP, and soil quality with a minimum yield penalty. Overall, the biochars not only boosted the soil C content and nutrient availability but also increased moisture content with better soil porosity. The addition of biochar in AWD irrigation is could be an efficient management system for improved rice yield with improved WP.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENINGKATAN HASIL PADI (*Oryza sativa* L.) DAN SIFAT FIZIK-KIMIA TANAH TERPILIH DENGAN MENGGUNAKAN BAHAN PEMBAIKPULIHTANAH ORGANIK BERSAMA PENGAIRAN JIMAT AIR

Oleh

AHMAD NUMERY ASHFAQUL HAQUE

April 2022

Pengerusi : Profesor Madya Md Kamal Uddin, PhD
Fakulti : Pertanian

Beras telah membekalkan kalori kepada lebih daripada separuh penduduk dunia, tetapi ianya memerlukan air yang lebih banyak berbanding tanaman ruji yang lain. Untuk meminimumkan penggunaan air yang berlebihan ini, amalan pengairan bergantian iaitu pembasahan dan pengeringan (AWD) adalah dianggap sebagai teknik yang berkesan terutama apabila tanah itu diairi secara berselang-seli. Penambahan bahan pembaikpulih tanah organik yang sesuai adalah dijangkakan akan dapat membantu mengekalkan kelembapan tanah dan meningkatkan sifat fizik-kimia tanah yang terlibat. Oleh itu dalam kajian ini, empat eksperimen telah dijalankan untuk menilai kesan pembaikpulih tanah organik ke atas sifat fizik-kimia tanah di dalam meningkatkan hasil padi padakeadaan pengairan yang menjimatkan air.Mulanyasatu kajian inkubasi telah dijalankan untuk menilai penggabungan lima bahan pembaikpulih organik terpilih—seperti berikut: biochar sekam padi (RHB), biochar tandan kosong sawit (EFBB), kompos, abu sekam padi (RHA), dan abu tandan sawit (PBA), bersamarawatan kawalan (tiada pemberiaan bahan pembaikpulih tanah) terhadap kelembapan simpanan tanah dan beberapa sifat kimia tanah. Tanah ini telah diinkubasi dengan lima pemberian bahan pembaikpulih selama 60 hari di mana sampel telah diambil pada selang masa 15 hari. Selepas tempoh inkubasi selesai, RHB (0.46 g g^{-1}) dan EFBB (0.45 g g^{-1}) telah menunjukkan kandungan air gravimetrik yang lebih tinggi berbanding dengan rawatan kawalan (0.16 g g^{-1}). Rawatan PBA telah menghasilkan pH tanah yang maksimum (6.95) berbanding nilai awalnya (5.01). Rawatan EFBB pada akhirnya telah menyumbang kepada peningkatan jumlah karbon (7.82%) dan nitrogen (0.44%) tertinggi.Rawatan PBA pula menunjukkan kandungan fosforus (P) dan kalium yang boleh ditukarganti tertinggi (K). Kajian kedua telah dijalankan untuk meneliti kesan pengairan jimat air bersama biochar dan kompos ke atas pertumbuhan, hasil, produktiviti air padi dan sifat fizik-kimia tanah.Eksperimen di dalam rumah kaca telah dijalankan dengan melibatkan dua rejim pengairan iaitu AWD dan air yang ditakungkan secaraberterusan (CF) bersama empat jenis rawatan termasuk tiga pembaikpulih organik iaitu RHB, EFBB, kompos yang digunakan pada 4% (berat/berat), dan dos baja disyorkan (RFD). Di bawah rejim pengairan AWD, bijirin maksimum telah dihasilkan oleh RHB (241.12 g) dan yang terendah pula adalah dari rawatan RFD (210.15 g), manakala bagi rawatan pembaikpulih organik yang sama, kedua-dua regim pengairan iaitu AWD dan CF telah memberikan hasil bijirin yang serupa. Rawatan RHB dan EFBB dengan pengairan AWD menunjukkan produktiviti air (WP) yang lebih baik (masing-masing 6.30 g L^{-1} dan 5.80 g L^{-1}) berbanding rawatan kawalan iaitu CF (3.94 g L^{-1}). Tanah yang diberikan pengairansamamenunjukkan nilai pH, keupayaan pertukaran kation, jumlah karbon (C), dan nitrogen (N) adalah lebih tinggi dengan penambahan biochar dan kompos di dalam rawatan kepada tanah berkenaan. Rawatan RHB dan EFBB telah berjaya mengurangkan ketumpatan pukal tanah dengan ketara sehingga 0.88 g cm^{-3} daripada 1.12 g cm^{-3} dan telah meningkatkan keliangan sehingga 58.7% berbanding RFD dalam pengairan CF. Kajian seterusnya dijalankan untuk meneliti kesan biochar ke atas hasil padi, kecekapan penggunaan baja N, dan pemulihan di bawah pengairan jimat air melalui penggunaan bahan pengesan isotop ^{15}N. Dua jenis pengairan AWD dan CF, dan empat jenis rawatan biochar seperti RHB dengan urea ^{15}N, EFBB dengan urea ^{15}N, urea yang diberikan ^{15}N sahaja, dan rawatan kawalantelah digunakan dalam kajian ini. Kira-kira 4% pengurangan hasil bijirin (193.89 g $pasu^{-1}$) telah dicapai oleh rejim AWD berbanding CF (202.57 g $pasu^{-1}$), manakala bagi rawatan RHB dan EFBB dengan urea ^{15}N telah berjaya meningkatkan hasil padi dengan ketara (sehingga 8.8%) berbanding rawatan urea ^{15}N sahaja. Rawatan RHB dan EFBB dengan urea ^{15}N telah meningkatkan pemulihan baja N daripada urea ^{15}N (masing-masing 0.59 gg^{-1} dan 0.61 g g^{-1}), melebihi ^{15}N urea sahaja (0.49 g g^{-1}). Kecekapan penggunaan agronomik dan produktiviti faktor separa N telah dipercepatkan dengan penambahan RHB (masing-masing 32.77 g g^{-1} dan 73.14 gg^{-1}) dan EFBB (33.77 g g^{-1} dan 74.14 g g^{-1}). Eksperimen terakhir telah dijalankan untuk menilai kesan biochar yang diberikan secara bersama dengan baja ke atas tindak balas fisiologi, WP dan kecekapan penggunaan nutrien (NUE) padi, dan perubahan sifat biokimia tanah di bawah pengairan AWD. Dua jenis amalan pengairan seperti AWD dan CF dan empat jenis gabungan baja iaitu T1: 25% RHB+75% daripada dos baja yang disyorkan (RFD), T2: 25% EFBB+75% daripada RFD, T3: 100% RFD, dan T0: 0% biochar dan 0% baja telah diberikan. Pengairan AWD menghasilkan hasil bijirin yang berkurangan secara mendadak (210.58 g $pasu^{-1}$) berbanding dengan pengairan CF (218.04 g $pasu^{-1}$), manakala bagi rawatan penggabungan biochar T1 dan T2 menghasilkan hasil yang lebih besar (260.27 g $pasu^{-1}$ dan 252.12 g $pasu^{-1}$, masing-masing), sehingga 12.5% lebih tinggi daripada RFD (231.27 g $pasu^{-1}$). Dalam tanah yang diberikan rawatan AWD, penggunaan air pengairan bagi T1 dan T2 (masing-masing 98.50 L dan 102.38 L) telah berjaya dikurangkan dengan ketara sehingga 28.8% berbanding CF dengan T3 (138.25 L), manakala WP pula telah dipertingkatkan. Kesan utama rawatan biochar T1 dan T2 juga berjaya meningkatkan kadar fotosintesis (masing-masing 21.31 dan 20.950 $\mu mol\ m^{-2}s^{-1}$) berbanding RFD (masing-masing 17.63 $\mu mol\ m^{-2}s^{-1}$), di samping meningkatkan kecekapan agronomik N, P dan K berbanding RFD. T1 dan T2 juga telah berjaya meningkatkan jumlah karbon dan nitrogen dengan ketara. Aktiviti enzim dehydrogenase dan urease juga telah meningkat dalam kedua-dua rejim pengairan. Hasil daripada kajian telahmenunjukkan bahawa pemberiansecara bersepadu RHB dan EFBB dengan rejim AWD adalah sangat berkesan untuk mengurangkan air pengairan dan meningkatkan NUE, WP, dan kualiti tanah dengan penalti hasil yang sangat minimum. Secara keseluruhannya, biochar bukan sahaja meningkatkan kandungan C tanah dan ketersediaan nutrien tetapi ianya juga mampu meningkatkan kandungan kelembapan dengan keliangan tanah yang lebih baik. Penambahan biochar dalam pengairan AWD boleh menjadi sistem pengurusan yang cekap untuk meningkatkan hasil padi dengan peningkatan WP.

ACKNOWLEDGEMENTS

First and foremost, I am extremely thankful to Almighty ALLAH for allowing me to accomplish my research thesis within the specified time frame. I would like to express my profound gratitude, heartfelt regard, sincere admiration, and obligation to my respected supervisor. Associate Professor Dr. Md Kamal Uddin, Department of Land Management, Universiti Putra Malaysia, for his effective and scholastic direction, compassionate supervision, great attention, consistent inspiration, and constructive criticism and recommendations throughout the whole term of research activity. I humbly desire to express my deep appreciation and gratitude to co-supervisors, Dr. Muhammad Firdaus Bin Sulaiman, Dr. Adibah Mohd Amin, and Professor Dr. Mahmud Hossain, for their guidance and encouragement.

I would also like to give special thanks to Bangladesh Agricultural Research Council (BARC) for the financial assistance awarded by the PhD Fellowship Programme of the National Agricultural Technology Program Phase-II (NATP-2) Project.

With due pleasure, I wish to convey my thanks to the staff of glasshouse of the Agriculture Faculty and Department of Land Management, Universiti Putra Malaysia, for their support and friendliness during the study. Last but not the least, I like to express my heartfelt thanks to my colleagues Md. Azadul Haque and Mohammad Asad Ullah for their co-operation.

This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirements for the degree of Doctor of Philosophy. The members of Supervisory Committee were as follows:

Md Kamal Uddin, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Muhammad Firdaus bin Sulaiman, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Adibah Mohd Amin, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Mahmud Hossain Sumon, PhD
Professor
Department of Soil Science
Bangladesh Agricultural University
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 July 2022

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________

Name of Chairman of Supervisory Committee: Associate Professor Dr. Md Kamal Uddin

Signature: ______________________________

Name of Member of Supervisory Committee: Dr. Muhammad Firdaus bin Sulaiman

Signature: ______________________________

Name of Member of Supervisory Committee: Dr. Adibah Mohd Amin

Signature: ______________________________

Name of Member of Supervisory Committee: Professor Dr. Mahmud Hossain Sumon

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ANOVA	Analysis of variance
AWD	Alternate wetting and drying
CF	Continuous flooding
CNS	Carbon, Nitrogen and Sulphur
EFBB	Oil empty fruit bunch biochar
FAO	Food and Agriculture Organization
ICP-OES	Inductively coupled plasma emission spectrometry
IRMS	Isotope ratio mass spectrometer
IRRI	International Rice Research Institute
MARDI	Malaysian Agricultural Research And Development Institute
^{15}N	N-15 isotope
RHA	Rice husk ash
PBA	Oil palm bunch ash
PVC	Polyvinyl chloride
RHB	Rice husk biochar
SEM	Scanning electron microscopy
SOM	Soil Organic Matter
SOC	Soil Organic Carbon
SPAD	Soil Plant Analysis Development
TDR	Time Domain Reflectometry
TPF	Triphenyl formazan
USDA	United States Department of Agriculture

UTM	Universal Transverse Mercator
p-NPP	Para-nitrophenyl phosphate

LIST OF SYMBOLS

kV	Kilvolt
mmol	Millimole
nm	Nanometer
w/w	Weight by weight ratio
µg	Microgram
µmol	Micromole
µm	Micrometer
^{13}C	Carbon-13 isotope
^{15}N	Nitrogen-15 isotope
‰	Parts per thousand

CHAPTER 1

INTRODUCTION

1.1 Background

Rice (*Oryza sativa* L.) is the staple food for almost 50% of the world's total population, the majority of them living in developing nations (Khan et al., 2016). Rice covers about 11% of the world's cropland (Tumrani et al., 2015). In 2017, rice covered over 160 million ha of land producing approximately 748 million tons of rice globally (FAO, 2018a). Generally, there are two types of rice produced in Malaysia, paddy rice and upland rice. Paddy rice is mostly planted in Peninsular Malaysia while upland rice is mostly planted in Sabah and Sarawak (Sohrabi et al., 2012).Malaysia expects to enhance its rice self-sufficiency more than 75% by 2025, thus it intends to improve rice-growing land, boost rice yield, or a blend of the two (Panhwar et al., 2016). However, Malaysia still relies on irrigated paddy rice with extensive use of water (Chan et al., 2012). To reduce the consumption of water in rice production, a potential irrigation technique termed the alternate wetting and drying (AWD) can reduce up to 43% of irrigation water without significant yield loss (Lampayan et al., 2015; Yao et al., 2012). In the AWD irrigation system, after the flooding of the field, the water levels decrease gradually, and when this level drops beneath 15 cm from the soil surface, the field is re-flooded to a 5 cm ponding water depth (Lampayan et al., 2015). A perforated pipe is used to monitor the water level below the soil surface. Previous studies on the effect of AWD on yield compared to other rice cultivation practices have reported varying effects, from a reduction in yield to increases in yield (Carrijo et al., 2017; Howell et al., 2015; Khairi et al., 2016; Xu et al., 2015). AWD can reduce 15% to 30% of irrigation water compared to conventional flooded rice systems (Belder et al., 2005), but during the drying cycles of AWD plant faces moisture stress to some extent and absorb less nutrients compared to conventional flooded rice, resulting in reduced water productivity (Belder et al., 2005; Gordon et al., 2008). These phenomena may overlook the water-saving effectiveness of AWD irrigation. To address these challenges of AWD, the application of organic amendments into the soil has the potential to substantially improve soil physicochemical properties and soil water retention.

In the recent decade, the potentials of biochar as an organic amendment has become a research hotspot in the field of agriculture for sustainable soil management (Tan et al., 2017). This material is produced from organic waste pyrolyzed at high temperatures (300-800°C) under a depleted oxygen atmosphere. Their main characteristics are black in colour, carbonaceous, highly porous, and contains stable organic compounds (Zhang et al., 2016). Morphological characters and chemical properties of biochar varies with the type of biomass used as feedstock, pyrolyzing temperature and oxygen limiting conditions during biochar production (Mukherjee et al., 2011).

Rice mills produces large quantities of rice husk as a by-product, which can be converted to rice husk ash and rice husk biochar to be used as an organic amendment to enhance the physicochemical properties of soil (Ghorbani et al., 2019), Apart from rice, in Malaysia, the waste biomass from oil palm has great potential for producing biochar especially empty fruit bunch for its readily availability (Sukiran et al., 2011) and derivative ash produced from oil palm bunch is an efficient liming material and it also provides nutrients when applied to soil (Awodun et al., 2007).

Rice yield performance is to be considered as the key indicator to adopt a management practice; the positive effect of biochar on rice yield has been reported by several studies(Chen et al., 2021; Dong et al., 2015; Ullah et al., 2021). The previous studies by Chen et al. (2021) and Oladele et al. (2019) opined that incorporation of rice husk biochar potentially increased rice yield. Moreover, the application of empty fruit bunch biochar increased the rice yield by enhancing soil cation exchange capacity (CEC) and nutrient availability was also reported Bakar et al. (2015). Additionally, biochar profoundly increases leaf chlorophyll content and net photosynthesis rate (Huang et al., 2021; Nguyen et al., 2017). Biochar inclusion boosts soil nutrients in two ways: firstly, by adding nutrients to the soil, and secondly, by adsorbing nutrients from other sources (Rawat et al., 2019). The addition of biochar has a favorable impact on the soil ecosystem through carbon sequestration and nutrient cycling, as well as increased soil microbial activity and moisture retention in water-scarce conditions (Blanco-Canqui, 2021). Concurrently, biochar is characterized by high porosity, and application of this material into soil explicitly adds new pores and promotes the soil's physical properties including porosity, density, pore size distribution, water retention, and moisture content (Verheijen et al., 2010). Biochar can regulate soil water retention by modifying different physical properties of the soil such as by reducing bulk density enhancing soil aggregation, changing pore size distribution, and improving soil porosity (Novak et al., 2012). Likewise, compost is a widely used soil additive and a good source of organic matter, and it contains a wide range of essential plant nutrients as well as humic compounds (Maheshwari, 2014). Compost contains various plant nutrients, and adding it to the soil improves CEC and minimizes nutrient loss into the subsoil (Agegnehu et al., 2014). The beneficial effect of compost on soil physical properties such as reducing bulk density, increasing porosity, enhancing hydraulic conductivity and plant available water were reported by Kranz et al. (2020).

1.2 Problem statement

In Malaysia, the agriculture sector uses approximately 68% of total water usage, whereas the irrigation efficiency varies from below 40 to 50% in the context of small to large irrigation schemes (Toriman & Mokhtar, 2012). Malaysia continues to rely on irrigated wetland paddy for rice production; while the yield of wetland rice is higher, though it takes a lot of water to keep the field inundated (Chan et al., 2012). So, it is crucial to establish the AWD irrigation to discard the excess water required to keep the field continuously flooded for lowland rice production and improve the water productivity of rice. But in AWD irrigation, the soil undergoes significant modifications when it switches from flooded to non-flooded regimes (Lampayan et al., 2015); these alternate changes cause a rather substantial alteration in the soil physiochemical environment (Alhaj Hamoud et al., 2018). Consecutively, AWD produces greater oxidizing conditions in the soil, which increases the microbial breakdown of plant waste and organic compounds in the soil (Oliver et al., 2019). Additionally, heterotrophic respiration of soil microbes takes place during the dry stage of AWD, causing enhanced mineralization of soil organic carbon (Moyano et al., 2013), and the enhanced activity of denitrifying bacteria accelerates the release of oxides of N by the denitrification process (Hoang et al., 2019). However, nutrient absorption of rice under AWD varies from that in continuous flooding (CF) due to the physiological response of rice to water stress and nutrition available in the AWD technique (Yang et al., 2004).Furthermore, under the moisture stress situation of AWD, plant nutrients absorption is decreased compared to the CF irrigation system (Belder et al., 2005). While the CF irrigation modifies soil characteristics of paddy soil, allowing for better root penetration, it results in higher soluble nutrient concentration and lower nutrient losses compared to AWD irrigation (Gordon et al., 2008). The incorporation of organic amendments to overcome these limitations of AWD irrigation for sustainable rice production is the main challenge of this study. The management of organic amendments, such as biochar and compost in AWD water-saving irrigation practice to maintain soil physicochemical properties for improved rice yield with better environmental quality is the main significance of this study of this research. Considering the issues, this study implies "Does organic amendments enhances the rice yield and water productivity with improved soil properties under the AWD irrigation systems?"

Therefore, it was hypothesized that the application of selected organic amendments i.e., rice husk biochar, rice husk ash, oil palm empty fruit bunch biochar, oil palm bunch ash and compost—may enhance the growth and yield performance of rice, consecutively enhancing the soil moisture and physicochemical properties of soil under AWD irrigation. To test the hypotheses, four experiments were conducted with the following objectives:

1.3 Specific objectives of the study

i. To determine the structural and chemical properties of compost and biochar, ash produced from rice husk, oil palm empty fruit bunch and to compare their potential to conserve moisture and changing soil chemical properties.

ii. To determine the effects of selected organic amendment under AWD on rice yield; and changes in soil physicochemical properties.

iii. To assess the effect of selected organic amendment on rice yield under AWD irrigation, their effect on nitrogen use efficiency and fertilizer N recovery using ^{15}N tracer.

iv. To observe the effects of integrated use of selected organic amendment and fertilizer on rice yield, physiological parameters and nutrient use efficiency under AWD irrigation, and their effect on and soil chemical properties and selected enzymatic activities.

1.4 Structure of Thesis

The format of this thesis follows Universiti Putra Malaysia's alternative thesis format, which is based on journal publishing. Every research chapter (journal manuscript) is divided into four sections: introduction, materials and methods, results and discussion, and conclusions. The following are the details of the thesis structure:

Chapter 1

Background of the study, problem statement and specific objective of the study presented in this chapter.

Chapter 2

This chapter provides a detailed assessment of the literature review on the subject matter of this study. Furthermore, the research gaps identified throughout the review were emphasized inside the chapter.

Chapter 3

This chapter describes the methods applied in this research for material preparation, experimental procedures, and data collection.

Chapter 4

The first article is presented in this chapter ''**Assessing the increase in soil moisture storage capacity and nutrient enhancement of different organic amendments in paddy soil**''. In this article, moisture retention capacity and nutrient release of five selected organic amendments at different days of incubation in a paddy soil was determined.

Chapter 5

From chapter-4 three organic amendments (rice husk biochar, oil palm biochar and compost) was screened for second experiment (Chapter-5) on basis of water storage, carbon and nitrogen content. The second article is presented in this chapter **''Impact of organic amendment with alternate wetting and drying (AWD) irrigation on rice yield, water productivity and physicochemical properties of soil**''. In this article, effect of biochar and compost with alternate wetting and drying irrigation on rice yield, water productivity and physicochemical properties of soil was evaluated.

Chapter 6

On the basis of improved rice yield and soil physicochemical properties two biochars (RHB and EFBB) were selected from second study (Chapter 5) to combined them with ^{15}N urea to study the nitrogen use efficiency and recovery for third experiment (Chapter 6) entitled ''**Combined use of biochar with ^{15}Nitrogen labelled urea increases rice yield, N use efficiency and fertilizer N recovery under water-saving irrigation**''. In this article, the influence of rice husk (RHB) and oil palm empty fruit bunch biochar (EFBB) on rice yield, fertilizer nitrogen (N) use efficiency and recovery under AWDusing^{15}N isotopic tracer was examined.

Chapter 7

Studies on fertilizer nitrogen recovery and efficiency from third experiment (Chapter 6); on the basis of nitrogen content, 25% of nutrient supplemented from RHB and EFBB with 75% of chemical fertilizer in the fourth experiment (Chapter 6) The fourth article is presented in this chapter ''**Rice growth performance, nutrient use efficiency of rice and changes in soil properties influenced by biochar under alternate wetting and drying irrigation**''. In this article, the effect of integrated application of RHB and EFBB with fertilizer on physiological response, water and nutrient efficiency of rice and changes in biochemical properties of soil under AWD was determined.

Chapter 8

This chapter summarizes the entire conclusion of the whole research as well as recommendation for future research.

REFERENCES

Abbasi, M. K., Afsar, N., & Rahim, N. (2013). Effect of wood ash and compost application on nitrogen transformations and availability in soil-plant systems. *Soil Science Society of America Journal*, *77*(2), 558–567. https://doi.org10.2136/sssaj2012.0365

Abdulrahman, D. K., Othman, R., & Saud, H. M. (2016). Effects of empty fruit bunch biochar and nitrogen-fixing bacteria on soil properties and growth of sweet corn. *Malaysian Journal of Soil Science*, *8*, 177–194.

Abrishamkesh, S., Gorji, M., Asadi, H., GH, B.-M., & AA, P. (2016). Effects of rice husk biochar application on the properties & amp;nbsp;of alkaline soil and lentil growth. *Plant, Soil and Environment*, *61*(No. 11), 475–482. https://doi.org/10.17221/117/2015-PSE

Agegnehu, G., VanBeek, C., & Bird, M. I. (2014). Influence of integrated soil fertility management in wheat and tef productivity and soil chemical properties in the highland tropical environment. *Journal of Soil Science and Plant Nutrition*, *ahead*, 0–0. https://doi.org/10.4067/S0718-95162014005000042

Ahmad, M., Lee, S. S., Dou, X., Mohan, D., Sung, J.-K., Yang, J. E., & Ok, Y. S. (2012). Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. *Bioresource Technology*, *118*, 536–544. https://doi.org/10.1016/j.biortech.2012.05.042

Alberto, M. C. R., Wassmann, R., Buresh, R. J., Quilty, J. R., Correa, T. Q., Sandro, J. M., & Centeno, C. A. R. (2014). Measuring methane flux from irrigated rice fields by eddy covariance method using open-path gas analyzer. *Field Crops Research*, *160*, 12–21. https://doi.org/10.1016/j.fcr.2014.02.008

Aldesuquy, H., Baka, Z., & Mickky, B. (2013). Does exogenous application of kinetin and spermine mitigate the effect of seawater on yield attributes and biochemical aspects of grains. *Journal of Stress Physiology & Biochemistry*, *9*, 21–34.

Alghamdi, A. G. (2018). Biochar as a potential soil additive for improving soil physical properties—a review. *Arabian Journal of Geosciences*, *11*(24), 766. https://doi.org/10.1007/s12517-018-4056-7

Alhaj Hamoud, Y., Guo, X., Wang, Z., Chen, S., & Rasool, G. (2018). Effects of irrigation water regime, soil clay content and their combination on growth, yield, and water use efficiency of rice grown in South China. *International Journal of Agricultural and Biological Engineering*, *11*(4), 126–136. https://doi.org/10.25165/j.ijabe.20181104.3895

Alhaj Hamoud, Y., Wang, Z., Guo, X., Shaghaleh, H., Sheteiwy, M., Chen, S., Qiu, R., & Elbashier, M. (2019). Effect of irrigation regimes and soil texture on the potassium utilization efficiency of rice. *Agronomy*, *9*(2), 100. https://doi

.org/10.3390/agronomy9020100

Ali, I., He, L., Ullah, S., Quan, Z., Wei, S., Iqbal, A., Munsif, F., Shah, T., Xuan, Y., Luo, Y., Tianyuan, L., & Ligeng, J. (2020a). Biochar addition coupled with nitrogen fertilization impacts on soil quality, crop productivity, and nitrogen uptake under double cropping system. *Food and Energy Security*, *9*(3). https://doi.org/10.1002/fes3.208

Ali, I., Ullah, S., He, L., Zhao, Q., Iqbal, A., Wei, S., Shah, T., Ali, N., Bo, Y., Adnan, M., Amanullah, & Jiang, L. (2020b). Combined application of biochar and nitrogen fertilizer improves rice yield, microbial activity and N-metabolism in a pot experiment. *PeerJ*, *8*, e10311. https://doi.org/10.7717/peerj.10311

Amin, A. E.-E. A. Z., & Eissa, M. A. (2017). Biochar effects on nitrogen and phosphorus use efficiencies of zucchini plants grown in a calcareous sandy soil. *Journal of Soil Science and Plant Nutrition*, *17*(4), 912–921. https:// doi.org /10.4067/S0718-95162017000400006

Anderson, C. R., Condron, L. M., Clough, T. J., Fiers, M., Stewart, A., Hill, R. A., & Sherlock, R. R. (2011). Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia*, *54*(5–6), 309–320. https://doi.org/10.1016/j.pedobi.2011.07.005

Arif, M., Ilyas, M., Riaz, M., Ali, K., Shah, K., Ul Haq, I., & Fahad, S. (2017). Biochar improves phosphorus use efficiency of organic-inorganic fertilizers, maize-wheat productivity and soil quality in a low fertility alkaline soil. *Field Crops Research*, *214*, 25–37. https://doi.org/10.1016/j.fcr.2017.08.018

Arnold, J. G., Potter, K. N., King, K. W., & Allen, P. M. (2005). Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. *Hydrological Processes*, *19*(3), 589–603. https://doi.org/10.1002/hyp.5609

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., & Horie, T. (2009). Biochar amendment techniques for upland rice production in Northern Laos. *Field Crops Research*, *111*(1–2), 81–84. https://doi.org/10. 1016/j.fcr.2008.10.008

Ashraf, M., & Waheed, A. (1990). Screening of local/exotic accessions of lentil (Lens culinaris Medic.) for salt tolerance at two growth stages. *Plant and Soil*, *128*(2), 167–176. https://doi.org/10.1007/BF00011106

Awodun, M. A., Ojeniyi, S. O., Adeboye, A., & Odedina, S. A. (2007). Effect of oilpalm bunch refuse ash on soil and plant nutrient composition and yield of maize. *American-Eurasian Journal of Sustainable Agriculture*, 50+.

Bakar, R. A., Razak, Z. A., Ahmad, S. H., Seh-Bardan, B. J., Tsong, L. C., & Meng, C. P. (2015). Influence of oil palm empty fruit bunch biochar on floodwater ph and yield components of rice cultivated on acid sulphate soil under rice intensification practices. *Plant Production Science*, *18*(4), 491–500. https://

doi.org/10.1626/pps.18.491

Ball, B. C., & Smith, K. A. (1991). Gas movement. In M. C. Smith KA (Ed.), *Soil analysis: physical methods* (pp. 511–549). Marcel Dekker.

Ball, P. N., MacKenzie, M. D., DeLuca, T. H., & Montana, W. E. H. (2010). Wildfire and charcoal enhance nitrification and ammonium-oxidizing bacterial abundance in dry montane forest soils. *Journal of Environmental Quality*, *39*(4), 1243–1253. https://doi.org/10.2134/jeq2009.0082

Barton, L., & Colmer, T. D. (2006). Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. *Agricultural Water Management*, *80*(1–3), 160–175. https://doi.org/10.1016/j.agwat.2005.07.011

Basso, A. S., Miguez, F. E., Laird, D. A., Horton, R., & Westgate, M. (2013). Assessing potential of biochar for increasing water-holding capacity of sandy soils. *GCB Bioenergy*, *5*(2), 132–143. https://doi.org/10.1111/gcbb.12026

Batista, E. M. C. C., Shultz, J., Matos, T. T. S., Fornari, M. R., Ferreira, T. M., Szpoganicz, B., de Freitas, R. A., & Mangrich, A. S. (2018). Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. *Scientific Reports*, *8*(1), 10677. https://doi.org /10.1038/s41598-018-28794-z

Bayu, D., Tadesse, M., & Amsalu, N. (2016). Effect of biochar on soil properties and lead (Pb) availability in a military camp in South West Ethiopia. *African Journal of Environmental Science and Technology*, *10*(3), 77–85. https://doi.org/10.5897/AJEST2015.2014

Beck, D. A., Johnson, G. R., & Spolek, G. A. (2011). Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution*, *159*(8–9), 2111–2118. https://doi.org/10.1016/j.envpol.2011.01.022

Beesley, L., & Dickinson, N. (2011). Carbon and trace element fluxes in the pore water of an urban soil following greenwaste compost, woody and biochar amendments, inoculated with the earthworm Lumbricus terrestris. *Soil Biology and Biochemistry*, *43*(1), 188–196. https:// doi.org/10.1016/j.soilbio.2010. 09.035

Beesley, L., Moreno-Jiménez, E., & Gomez-Eyles, J. L. (2010). Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environmental Pollution*, *158*(6), 2282–2287. https://doi.org/10.1016//J.ENVPOL.2010.02.003

Belder, P., Bouman, B. A. ., Cabangon, R., Guoan, L., Quilang, E. J. ., Yuanhua, L., Spiertz, J. H. ., & Tuong, T. . (2004). Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agricultural Water Management*, *65*(3), 193–210. https://doi.org/10.1016/j.agwat.2003.09.002

Belder, P., Spiertz, J. H. J., Bouman, B. A. M., Lu, G., & Tuong, T. P. (2005). Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crops Research*, *93*(2–3), 169–185. https://doi.org/10.1016/j.fcr.2004.09.022

Benton, J. J. (2001). *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. CRC Press. https://doi.org/10.1201/9781420025293

Bhaduri, D., Saha, A., Desai, D., & Meena, H. N. (2016). Restoration of carbon and microbial activity in salt-induced soil by application of peanut shell biochar during short-term incubation study. *Chemosphere*, *148*, 86–98. https://doi.org/10.1016/j. chemosphere.2015.12.130

Bhattacharyya, P. and D. B. (2018). Crop residue management and greenhouse gases emissions in tropical rice lands. In M. Á. M. and R. Zornoza (Ed.), *Soil management and climate change* (pp. 323–335). Academic Press.

Bian, R., Zhang, A., Li, L., Pan, G., Zheng, J., Zhang, X., Zheng, J., Joseph, S., & Chang, A. (2013). Effect of municipal biowaste biochar on greenhouse gas emissions and metal bioaccumulation in a slightly acidic clay rice paddy. *BioResources*, *9*(1), 685–703.

Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy*, *5*(2), 202–214. https://doi.org/10.1111/gcbb.12037

Blackwell, P., Joseph, S., Munroe, P., Anawar, H. M., Storer, P., Gilkes, R. J., & Solaiman, Z. M. (2015). Influences of biochar and biochar-mineral complex on mycorrhizal colonisation and nutrition of wheat and sorghum. *Pedosphere*, *25*(5), 686–695. https://doi.org/10.1016/S1002-0160(15)30049-7

Blake, G. R. (2008). Particle density. In W. Chesworth (Ed.), *Encyclopedia of soil science* (pp. 504–505). Springer Netherlands. https://doi.org/10.1007/978-1-4020-3995-9_406

Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, *81*(4), 687–711. https://doi.org/10.2136/sssaj2017.01.0017

Blanco-Canqui, H. (2021). Does biochar improve all soil ecosystem services? *GCB Bioenergy*, *13*(2), 291–304. https://doi.org/10.1111/gcbb.12783

Bolan, N. S., Adriano, D. C., Kunhikrishnan, A., James, T., McDowell, R., & Senesi, N. (2011). *Dissolved Organic Matter* (pp. 1–75). https://doi.org/10.1016/B978-0-12-385531-2.00001-3

Bonanomi, G., Ippolito, F., Cesarano, G., Nanni, B., Lombardi, N., Rita, A., Saracino, A., & Scala, F. (2017). Biochar as plant growth promoter: better off alone or mixed with organic amendments? *Frontiers in Plant Science*, *8*. https://doi.org/10.3389/fpls.2017.01570

Bonfim-Silva, E. M., Bezerra, M. D. L., Silva, T. J. A. da, Fenner, W., & Damasceno, A. P. A. B. (2019). Wood ash and water availability in the production of Paiaguás-grass. *Ambiente e Agua - An Interdisciplinary Journal of Applied Science*, *14*(6), 1. https://doi.org/10.4136/ambi-agua.2424

Bordoloi, S., Gopal, P., Boddu, R., Wang, Q., Cheng, Y.-F., Garg, A., & S, S. (2019). Soil-biochar-water interactions: Role of biochar from Eichhornia crassipes in influencing crack propagation and suction in unsaturated soils. *Journal of Cleaner Production*, *210*, 847–859. https://doi.org/10.1016/j.jclepro.2018.11.051

Borken, W., & Matzner, E. (2009). Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology*, *15*(4), 808–824. https://doi.org/10.1111/j.1365-2486.2008.01681.x

Bottinelli, N., Zhou, H., Boivin, P., Zhang, Z. B., Jouquet, P., Hartmann, C., & Peng, X. (2016). Macropores generated during shrinkage in two paddy soils using X-ray micro-computed tomography. *Geoderma*, *265*, 78–86. https://doi.org/10.1016/j.geoderma.2015.11.011

Bouman, B., Barker, R., Humphreys, E., Tuong, T. P., Atlin, G. N., Bennett, J., Dawe, D., Dittert, K., Dobermann, A., Facon, T., Fujimoto, N., Gupta, R., Haefele, S., Hosen, Y., Ismail, A., Johnson, D., Johnson, S., Khan, S., Shan, L., & Wassmann, R. (2007). Rice: Feeding the billion. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 515–549). Earthscan.

Bouman B.A.M, Hengsdijk H., Hardy B., Bindraban P.S., Tuong T.P., L. J. . (2002). Water-wise rice production. *International Workshop on Water-Wise Rice Production*, 356.

Bouman, B.A.M. (2007). A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agricultural Systems*, *93*(1–3), 43–60. https://doi.org/10.1016/j.agsy.2006.04.004

Bouman, B.A.M., Feng, L., Tuong, T. P., Lu, G., Wang, H., & Feng, Y. (2007). Exploring options to grow rice using less water in northern China using a modelling approach. *Agricultural Water Management*, *88*(1–3), 23–33. https://doi.org/10.1016/j.agwat.2006.10.005

Bouman, B.A.M, Lampayan, R. ., & Tuong, T. P. (2007). *Water management in irrigated rice. Coping with water scarcity* (B. Hardy (ed.)). International Rice Research Institute (IRRI).

Bouman, B.A.M, & Tuong, T. . (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, *49*(1), 11–30. https://doi.org/10.1016/S0378-3774(00)00128-1

Bouman, Bas A M, Barker, R., Humphreys, E., Tuong, T. P., Atlin, G., Bennett, J., Dawe, D., Dittert, K., Dobermann, A., & Facon, T. (2007). Rice: feeding the billions. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 515–549). Earthscan.

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, *59*(1).

Buresh, R. J., & Haefele, S. M. (2010). Changes in paddy soils under transition to water-saving and diversified cropping systems. In N. Gilkes, R. J., Prakongkep (Ed.), *Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world* (pp. 9–12).

Butterly, C. R., McNeill, A. M., Baldock, J. A., & Marschner, P. (2011). Rapid changes in carbon and phosphorus after rewetting of dry soil. *Biology and Fertility of Soils*, *47*(1), 41–50. https://doi.org/10.1007/s00374-010-0500-x

Carrijo, D. R., Akbar, N., Reis, A. F. B., Li, C., Gaudin, A. C. M., Parikh, S. J., Green, P. G., & Linquist, B. A. (2018). Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Research*, *222*, 101–110. https://doi.org/10.1016/j.fcr.2018.02.026

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*, *203*, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Case, S. D. C., McNamara, N. P., Reay, D. S., Stott, A. W., Grant, H. K., & Whitaker, J. (2015). Biochar suppresses N2O emissions while maintaining N availability in a sandy loam soil. *Soil Biology and Biochemistry*, *81*, 178–185. https://doi.org/10.1016/j.soilbio.2014.11.012

Casida, L. E., Klein, D. A., & Santoro, T. (1964). Soil dehydrogenase activity. *Soil Science*, *98*(6), 371–376. https://doi.org/10.1097/00010694-196412000-00004

Cassman, K. G., Peng, S., Olk, D. C., Ladha, J. K., Reichardt, W., Dobermann, A., & Singh, U. (1998). Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research*, *56*(1–2), 7–39. https://doi.org/10.1016/S0378-4290(97)00140-8

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., & Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*, *154*, 1–13. https://doi.org/10.1016/j.still.2015. 06.016

Cayuela, M. L., van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, *191*, 5–16. https://doi.org/10.1016/j.agee.2013.10.009

Centritto, M., Lauteri, M., Monteverdi, M. C., & Serraj, R. (2009). Leaf gas exchange, carbon isotope discrimination, and grain yield in contrasting rice genotypes subjected to water deficits during the reproductive stage. *Journal of Experimental Botany*, *60*(8), 2325–2339. https://doi.org/10.1093/jxb/erp123

Chalker-Scott, L. (2014). *Biochar : a home gardener's primer* (Fact Sheet (Washington State University. Cooperative Extension)). Washington State University. Extension.

Ch'ng, H. Y., Ahmed, O. H., & Majid, N. M. A. (2014). Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *The Scientific World Journal*, *2014*, 1–6. https://doi. org/ 10.1155/2014/506356

Chan, C. S., Zainudin, H., Saad, A. R., & Azmi, M. A. (2012). Productive water use in aerobic rice cultivation. *Journal of Tropical Agriculture and Food Science*, *40*, 117–126.

Chang, R., Jin, T., Lü, Y., Liu, G., & Fu, B. (2014). Soil carbon and nitrogen changes following afforestation of marginal cropland across a precipitation gradient in Loess Plateau of China. *PLoS ONE*, *9*(1), e85426. https://doi.org/10.1371/ journal.pone.0085426

Chen, C., Wang, R., Shang, J., Liu, K., Irshad, M. K., Hu, K., & Arthur, E. (2018). Effect of biochar application on hydraulic properties of sandy soil under dry and wet conditions. *Vadose Zone Journal*, *17*(1), 180101. https://doi.org/10.2136 /vzj2018.05.0101

Chen, L, Qiao, Z.-G., Li, L.-Q., & Pan, G.-X. (2013). Effects of biochar-based fertilizers on rice yield and nitrogen use efficiency. *Journal of Ecology and Rural Environment*, *29*, 671–675.

Chen, Le, Liu, M., Ali, A., Zhou, Q., Zhan, S., Chen, Y., Pan, X., & Zeng, Y. (2020a). Effects of biochar on paddy soil fertility under different water management modes. *Journal of Soil Science and Plant Nutrition*. https://doi.org/ 10.1007/s42729-020-00252-8

Chen, Le, Liu, M., Ali, A., Zhou, Q., Zhan, S., Chen, Y., Pan, X., & Zeng, Y. (2020b). Effects of biochar on paddy soil fertility under different water management modes. *Journal of Soil Science and Plant Nutrition*, *20*(4), 1810–1818. https://doi.org/10.1007/s42729-020-00252-8

Chen, X., Yang, S., Ding, J., Jiang, Z., & Sun, X. (2021). Effects of biochar addition on rice growth and yield under water-saving irrigation. *Water*, *13*(2), 209. https://doi.org/10.3390/w13020209

Claoston, N., Samsuri, A., Ahmad Husni, M., & Mohd Amran, M. (2014). Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars. *Waste Management & Research: The Journal for a*

Sustainable Circular Economy, *32*(4), 331–339. https://doi.org/10.1177/0734242X14525822

Clough, T., Condron, L., Kammann, C., & Müller, C. (2013). A review of biochar and soil nitrogen dynamics. *Agronomy*, *3*(2), 275–293. https://doi.org/10.3390/agronomy3020275

Clough, T. J., & Condron, L. M. (2010). Biochar and the nitrogen cycle: Introduction. *Journal of Environmental Quality*, *39*(4), 1218–1223. https://doi.org/10.2134/jeq2010.0204

Cooper, J. D. (2016). Gravimetric Method. In J. D. Cooper (Ed.), *Soil water measurement* (pp. 26–42). Wiley-Blackwell. https://doi.org/https://doi.org/10.1002/9781119106043.ch6

Currie, H. A., & Perry, C. C. (2007). Silica in Plants: Biological, Biochemical and Chemical Studies. *Annals of Botany*, *100*(7), 1383–1389. https://doi.org/10.1093/aob/mcm247

DeLuca, T. H., MacKenzie, M. D., Gundale, M. J., & Holben, W. E. (2006). Wildfire-produced charcoal directly influences nitrogen cycling in Ponderosa pine forests. *Soil Science Society of America Journal*, *70*(2), 448–453. https://doi.org/10.2136/sssaj2005.0096

Demir, Z., & Gülser, C. (2015). Effects of rice husk compost application on soil quality parameters in greenhouse conditions. *Eurasian Journal of Soil Science*, *4*(3), 185. https://doi.org/10.18393/ejss.2015.3.185-190

Denardin, L. G. de O., Alves, L. A., Ortigara, C., Winck, B., Coblinski, J. A., Schmidt, M. R., Carlos, F. S., Toni, C. A. G. de, Camargo, F. A. de O., Anghinoni, I., & Clay, D. (2020). How different soil moisture levels affect the microbial activity. *Ciência Rural*, *50*(6). https://doi.org/10.1590/0103-8478cr 20190831

Dey, A., Srivastava, P. C., Pachauri, S. P., & Shukla, A. K. (2019). Time-dependent release of some plant nutrients from different organic amendments in a laboratory study. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(S1), 173–188. https://doi.org/10.1007/s40093-019-0287-1

Ding, Y., Liu, Y., Liu, S., Huang, X., Li, Z., Tan, X., Zeng, G., & Zhou, L. (2017). Potential benefits of biochar in agricultural soils: A review. *Pedosphere*, *27*(4), 645–661. https://doi.org/10.1016/S1002-0160(17)60375-8

Dinka, T. M., & Lascano, R. J. (2012). Review Paper: Challenges and limitations in studying the shrink-swell and crack dynamics of Vertisol soils. *Open Journal of Soil Science*, *02*(02), 82–90. https://doi.org/10.4236/ojss.2012.22012

Djaman, K., Mel, V., Diop, L., Sow, A., El-Namaky, R., Manneh, B., Saito, K., Futakuchi, K., & Irmak, S. (2018). Effects of alternate wetting and drying irrigation regime and nitrogen fertilizer on yield and nitrogen use efficiency of irrigated rice in the Sahel. *Water*, *10*(6), 711. https://doi.org/10.3390/w10060 711

Dokoohaki, H., Miguez, F. E., Laird, D., Horton, R., & Basso, A. S. (2017). Assessing the biochar effects on selected physical properties of a sandy soil: an analytical approach. *Communications in Soil Science and Plant Analysis*, *48*(12), 1387–1398. https://doi.org/10.1080/00103624.2017.1358742

Dong, D., Feng, Q., McGrouther, K., Yang, M., Wang, H., & Wu, W. (2015). Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. *Journal of Soils and Sediments*, *15*(1), 153–162. https://doi.org/10.1007/s11368-014-0984-3

Dong, N. M., Brandt, K. K., Sørensen, J., Hung, N. N., Hach, C. Van, Tan, P. S., & Dalsgaard, T. (2012). Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biology and Biochemistry*, *47*, 166–174. https://doi.org/10.1016/j.soilbio.2011.12.028

Downie, A., Crosky, A. and Munroe, P. (2009). Biochar for environmental management, science and technology. In J. L. L. and J. S. Joseph (Ed.), *Physical properties of biochar* (pp. 13–32). Earthscan.

Du, Z., Chen, X., Qi, X., Li, Z., Nan, J., & Deng, J. (2016). The effects of biochar and hoggery biogas slurry on fluvo-aquic soil physical and hydraulic properties: a field study of four consecutive wheat–maize rotations. *Journal of Soils and Sediments*, *16*(8), 2050–2058. https://doi.org/10.1007/s11368-016-1402-9

Durenkamp, M., Luo, Y., & Brookes, P. C. (2010). Impact of black carbon addition to soil on the determination of soil microbial biomass by fumigation extraction. *Soil Biology and Biochemistry*, *42*(11), 2026–2029. https://doi.org/10.1016/j.soilbio.2010.07.016

El-Naggar, A., El-Naggar, A. H., Shaheen, S. M., Sarkar, B., Chang, S. X., Tsang, D. C. W., Rinklebe, J., & Ok, Y. S. (2019). Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. *Journal of Environmental Management*, *241*, 458–467. https://doi.org/10.1016/j.jenvman.2019.02.044

El-Naggar, A. H., Usman, A. R. A., Al-Omran, A., Ok, Y. S., Ahmad, M., & Al-Wabel, M. I. (2015). Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. *Chemosphere*, *138*, 67–73. https://doi.org/10.1016/j.chemosphere.2015.05.052

El-Naggar, A., Lee, S. S., Awad, Y. M., Yang, X., Ryu, C., Rizwan, M., Rinklebe, J., Tsang, D. C. W., & Ok, Y. S. (2018). Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. *Geoderma*, *332*, 100–108. https://doi.org/10.1016/j.geoderma.2018.06.017

Ennis, C. J., Evans, A. G., Islam, M., Ralebitso-Senior, T. K., & Senior, E. (2012). Biochar: Carbon Sequestration, Land Remediation, and Impacts on Soil Microbiology. *Critical Reviews in Environmental Science and Technology*, *42*(22), 2311–2364. https://doi.org/10.1080/10643389. 2011.574115

FAO. (2018). Rice market monitor. *Food and Agriculture Organization Proceedings*, 1–35.

Farquhar, G. D., Ehleringer, J. R., & Hubick, K. T. (1989). Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology*, *40*(1), 503–537. https://doi.org/10.1146/ annurev. pp.40.060189.002443

Feng, Z., Leung, L. R., Hagos, S., Houze, R. A., Burleyson, C. D., & Balaguru, K. (2016). More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. *Nature Communications*, *7*(1), 13429. https://doi. org/ 10.1038/ncomms13429

Fidel, R. B., Laird, D. A., Thompson, M. L., & Lawrinenko, M. (2017). Characterization and quantification of biochar alkalinity. *Chemosphere*, *167*, 367–373. https://doi.org/10.1016/j.chemosphere.2016.09.151

Flanagan, L. B., & Johnson, B. G. (2005). Interacting effects of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. *Agricultural and Forest Meteorology*, *130*(3–4), 237–253. https://doi.org/10.1016/j.agrformet.2005.04.002

Futa, B., Oleszczuk, P., Andruszczak, S., Kwiecińska-Poppe, E., & Kraska, P. (2020). Effect of natural aging of biochar on soil enzymatic activity and physicochemical properties in long-term field experiment. *Agronomy*, *10*(3), 449. https://doi.org/10.3390/agronomy10030449

Gamage, D. N. V., Mapa, R. B., Dharmakeerthi, R. S., & Biswas, A. (2016). Effect of rice-husk biochar on selected soil properties in tropical Alfisols. *Soil Research*, *54*(3), 302. https://doi.org/10.1071/SR15102

Gao, S., & DeLuca, T. H. (2016). Influence of biochar on soil nutrient transformations, nutrient leaching, and crop yield. *Advances in Plants & Agriculture Research*, *4*(5). https://doi.org/10.15406/apar.2016.04.00150

Gao, T., Gao, M., Peng, J., & Li, N. (2018). Effects of different amount of biochar on nitrogen, phosphorus and potassium nutrients in soil. *IOP Conference Series: Materials Science and Engineering*, *394*, 022043. https://doi.org/10.1088/1757-899X/394/2/022043

García, A. C., de Souza, L. G. A., Pereira, M. G., Castro, R. N., García-Mina, J. M., Zonta, E., Lisboa, F. J. G., & Berbara, R. L. L. (2016). Structure-property-function relationship in humic substances to explain the biological activity in plants. *Scientific Reports*, *6*(1), 20798. https://doi.org/10.1038/srep20798

Garg, K. K., Das, B. S., Safeeq, M., & Bhadoria, P. B. S. (2009). Measurement and modeling of soil water regime in a lowland paddy field showing preferential transport. *Agricultural Water Management*, *96*(12), 1705–1714. https://doi.org/10.1016/j.agwat.2009.06.018

Gazulla, M. F., Rodrigo, M., Orduña, M., & Gómez, C. M. (2012). Determination of carbon, hydrogen, nitrogen and sulfur in geological materials using elemental analysers. *Geostandards and Geoanalytical Research*, *36*(2), 201–217. https://doi.org/https://doi.org/10.1111/j.1751-908X.2011.00140.x

Ghorbani, M., Asadi, H., & Abrishamkesh, S. (2019). Effects of rice husk biochar on selected soil properties and nitrate leaching in loamy sand and clay soil. *International Soil and Water Conservation Research*, *7*(3), 258–265. https://doi.org/10.1016/j.iswcr.2019.05.005

Głąb, T., Palmowska, J., Zaleski, T., & Gondek, K. (2016). Effect of biochar application on soil hydrological properties and physical quality of sandy soil. *Geoderma*, *281*, 11–20. https://doi.org/10.1016/j.geoderma.2016.06.028

Glaser, B., & Lehr, V.-I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific Reports*, *9*(1), 9338. https://doi.org/10.1038/s41598-019-45693-z

Gordon, H., Haygarth, P. M., & Bardgett, R. D. (2008). Drying and rewetting effects on soil microbial community composition and nutrient leaching. *Soil Biology and Biochemistry*, *40*(2), 302–311. https://doi.org/10.1016/j.soilbio.2007.08.008

Gould, M. C. (2012). *Compost increases the water holding capacity of droughty soils*.

Gray, M., Johnson, M. G., Dragila, M. I., & Kleber, M. (2014). Water uptake in biochars: The roles of porosity and hydrophobicity. *Biomass and Bioenergy*, *61*, 196–205. https://doi.org/10.1016/j.biombioe.2013.12.010

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agriculture, Ecosystems & Environment*, *206*, 46–59. https://doi.org/10.1016/j.agee.2015.03.015

Haefele, S. M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A. A., Pfeiffer, E. M., & Knoblauch, C. (2011). Effects and fate of biochar from rice residues in rice-based systems. *Field Crops Research*, *121*(3), 430–440. https:// doi.org/10.1016/j.fcr.2011.01.014

Hale, S. E., Alling, V., Martinsen, V., Mulder, J., Breedveld, G. D., & Cornelissen, G. (2013). The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. *Chemosphere*, *91*(11), 1612–1619. https://doi.org/10.1016/j.chemosphere.2012.12.057

Hansen, V., Hauggaard-Nielsen, H., Petersen, C. T., Mikkelsen, T. N., & Müller-Stöver, D. (2016). Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. *Soil and Tillage Research*, *161*, 1–9. https://doi.org/10.1016/j.still.2016.03.002

Haque, A. N. A, Uddin, M. K., Sulaiman, M. F., Amin, A. M., Hossain, M., Aziz, A. A., & Mosharrof, M. (2021a). Impact of organic amendment with alternate wetting and drying irrigation on rice yield, water use efficiency and physicochemical properties of soil. *Agronomy*, *11*(8), 1529. https://doi. org/10. 3390 /agronomy11081529

Haque, Ahmad Numery Ashfaqul, Uddin, M. K., Sulaiman, M. F., Amin, A. M., Hossain, M., Solaiman, Z. M., & Mosharrof, M. (2021b). Biochar with alternate wetting and drying irrigation: a potential technique for paddy soil management. *Agriculture*, *11*(4), 367. https://doi.org/10.3390/agriculture11040367

Haque, Ahmad Numery Ashfaqul, Uddin, M. K., Sulaiman, M. F., Amin, A. M., Hossain, M., Zaibon, S., & Mosharrof, M. (2021c). Assessing the increase in soil moisture storage capacity and nutrient enhancement of different organic amendments in paddy soil. *Agriculture*, *11*(1), 44. https://doi.org/10.3390/ agriculture11010044

Hardie, M., Clothier, B., Bound, S., Oliver, G., & Close, D. (2014). Does biochar influence soil physical properties and soil water availability? *Plant and Soil*, *376*(1–2), 347–361. https://doi.org/10.1007/s11104-013-1980-x

He, Yanghui, Yao, Y., Ji, Y., Deng, J., Zhou, G., Liu, R., Shao, J., Zhou, L., Li, N., Zhou, X., & Bai, S. H. (2020). Biochar amendment boosts photosynthesis and biomass in C 3 but not C 4 plants: A global synthesis. *GCB Bioenergy*, *12*(8), 605–617. https://doi.org/10.1111/gcbb.12720

He, Yao, Lehndorff, E., Amelung, W., Wassmann, R., Alberto, M. C., von Unold, G., & Siemens, J. (2017). Drainage and leaching losses of nitrogen and dissolved organic carbon after introducing maize into a continuous paddy-rice crop rotation. *Agriculture, Ecosystems & Environment*, *249*, 91–100. https://doi. org/10.1016/j.agee.2017.08.021

Herath, H. M. S. K., Camps-Arbestain, M., & Hedley, M. (2013). Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma*, *209–210*, 188–197. https://doi.org/10.1016/j.geoderma.2013.06.016

Hidayati, N., Triadiati, & Anas, I. (2016). Photosynthesis and transpiration rates of rice cultivated under the system of rice intensification and the effects on growth and yield. *Hayati Journal of Biosciences*, *23*(2), 67–72. https://doi.org/10. 1016/j.hjb.2016.06.002

Hirzel, J., Donnay, D., Fernández, C., Meier, S., Lagos, O., Mejias-Barrera, P., & Rodríguez, F. (2018). Evolution of nutrients and soil chemical properties of seven organic fertilizers in two contrasting soils under controlled conditions.

Chilean Journal of Agricultural and Animal Sciences, *38*(2), 77–88. https://doi.org/10.4067/S0719-38902018005000301

Hoang, T. T. H., Do, D. T., Tran, T. T. G., Ho, T. D., & Rehman, H. ur. (2019). Incorporation of rice straw mitigates CH_4 and N_2O emissions in water saving paddy fields of Central Vietnam. *Archives of Agronomy and Soil Science*, *65*(1), 113–124. https://doi.org/10.1080/03650340.2018.1487553

Hodson, M. J., White, P. J., Mead, A., & Broadley, M. R. (2005). Phylogenetic variation in the silicon composition of plants. *Annals of Botany*, *96*(6), 1027–1046. https://doi.org/10.1093/aob/mci255

Hospido, A., Moreira, T., Martín, M., Rigola, M., & Feijoo, G. (2005). Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes (10 pp). *The International Journal of Life Cycle Assessment*, *10*(5), 336–345. https://doi.org/10.1065/lca2005.05.210

Hottle, R. D. (2013). *Impact of biochar on plant productivity and soil properties under a maize soybean rotation on an Alfisol in Central Ohio*. The Ohio State University.

Howell, K. R., Shrestha, P., & Dodd, I. C. (2015). Alternate wetting and drying irrigation maintained rice yields despite half the irrigation volume, but is currently unlikely to be adopted by smallholder lowland rice farmers in Nepal. *Food and Energy Security*, *4*(2), 144–157. https://doi.org/10.1002/fes3.58

Huang, M., Yang, L., Qin, H., Jiang, L., & Zou, Y. (2014). Fertilizer nitrogen uptake by rice increased by biochar application. *Biology and Fertility of Soils*, *50*(6), 997–1000. https://doi.org/10.1007/s00374-014-0908-9

Huang, M., Yin, X., Chen, J., & Cao, F. (2021). Biochar application mitigates the effect of heat stress on rice (*Oryza sativa* L.) by regulating the root-zone environment. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/ fpls. 2021.711725

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., Ammara, U., Ok, Y. S., & Siddique, K. H. M. (2017). Biochar for crop production: potential benefits and risks. *Journal of Soils and Sediments*, *17*(3), 685–716. https://doi.org/10.1007/s11368-016-1360-2

Ippolito, J.A. and Spokas, K.A. and Novak, J.M. and Lentz, R.D. and Cantrell, K. B. (2015). Biochar elemental composition and factors influencing nutrient retention. In S. Lehmann, Johannes and Joseph (Ed.), *Biochar for envrionmental management: science, technolody and implementation* (pp. 137–161). Routledge.

IRRI. (2018). *Rice knowledge bank*.International rice research institute: Los Baños, Philippines, 2018.

Jaafar, N. M., Clode, P. L., & Abbott, L. K. (2015). Biochar-soil interactions in four agricultural soils. *Pedosphere*, *25*(5), 729–736. https://doi.org/10.1016/S1002-0160(15)30054-0

Jahangir, M. M. R., Khalil, M. I., Johnston, P., Cardenas, L. M., Hatch, D. J., Butler, M., Barrett, M., O'flaherty, V., & Richards, K. G. (2012). Denitrification potential in subsoils: A mechanism to reduce nitrate leaching to groundwater. *Agriculture, Ecosystems & Environment*, *147*, 13–23. https://doi.org/10.1016/j.agee.2011.04.015

Jat, H. S., Datta, A., Choudhary, M., Sharma, P. C., Dixit, B., & Jat, M. L. (2021). Soil enzymes activity: Effect of climate smart agriculture on rhizosphere and bulk soil under cereal based systems of north-west India. *European Journal of Soil Biology*, *103*, 103292. https://doi.org/10.1016/j.ejsobi.2021.103292

Javed, A., Ashraf, M. Y., Sabir, S. A., & Wajid, I. (2012). Use of carbon isotope discrimination technique to sustain rice productivity under stressed and low land irrigated ecosystem of Pakistan. *Pakistan Journal of Botany*, *44*, 85–93.

Jien, S.-H., & Wang, C.-S. (2013). Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena*, *110*, 225–233. https://doi.org/. 10.1016/j.catena.2013.06.021

Johannes Lehmann, S. J. (2015). *Biochar for environmental management: Science, technology and implementation* (S. J. Johannes Lehmann (ed.); Second). Taylor & Francis. https://doi.org/10.4324/9780203762264

Kaiser, K., & Kalbitz, K. (2012). Cycling downwards – dissolved organic matter in soils. *Soil Biology and Biochemistry*, *52*, 29–32. https://doi.org/10.1016/j.soil bio.2012.04.002

Kalia, V. C., Gong, C., Patel, S. K. S., & Lee, J.-K. (2021). Regulation of plant mineral nutrition by signal molecules. *Microorganisms*, *9*(4), 774. https://doi. org /10.3390/microorganisms9040774

Kameyama, K., Miyamoto, T., & Shiono, T. (2014). Influence of biochar incorporation on TDR-based soil water content measurements. *European Journal of Soil Science*, *65*(1), 105–112. https://doi.org/10.1111/ejss.12083

Kameyama, K., Miyamoto, T., Shiono, T., & Shinogi, Y. (2012). Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil. *Journal of Environmental Quality*, *41*(4), 1131–1137. https://doi.org/10.2134/jeq2010.0453

Kameyama, Koji, Miyamoto, T., & Iwata, Y. (2019). The preliminary study of water-retention related properties of biochar produced from various feedstock at different pyrolysis temperatures. *Materials*, *12*(11), 1732. https://doi.org/ /ma12111732

Kameyama, Koji, Miyamoto, T., Iwata, Y., & Shiono, T. (2016). Effects of biochar produced from sugarcane bagasse at different pyrolysis temperatures on water retention of a calcaric dark red soil. *Soil Science*, *181*(1), 20–28. https://doi.org/10.1097/SS.0000000000000123

Karim, A. A., Kumar, M., Singh, S. K., Panda, C. R., & Mishra, B. K. (2017). Potassium enriched biochar production by thermal plasma processing of banana peduncle for soil application. *Journal of Analytical and Applied Pyrolysis*, *123*, 165–172. https://doi.org/10.1016/j.jaap.2016.12.009

Keeney, D. R., & Nelson, D. W. (1983). Nitrogen—Inorganic Forms. In *Methods of Soil Analysis* (pp. 643–698). https://doi.org/https://doi.org/10.2134/agronmo nogr 9.2.2ed.c33

Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science & Technology*, *44*(4), 1247–1253. https://doi.org/10.1021/es9031419

Khairi, M., Nozulaidi, M., & Md Sarwar, J. (2016). Effects of flooding and alternate wetting and drying on the yield performance of upland rice. *Pertanika Tropical Agricultural Science*, *39*(3), 299–309.

Khan, A., Shams-ul, T., Iqbal, A., & Fahad, S. (2016). Growth and productivity response of hybrid rice to application of animal manures, plant residues and phosphorus. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.01440

Khan, M., & Shah, M. R. (2007). Sorption kinetics of water vapours in chromatographic silica gel. *Journal- Chemical Society of Pakistan*, *29*(3), 209–212.

Khan, S., Chao, C., Waqas, M., Arp, H. P. H., & Zhu, Y.-G. (2013). Sewage Sludge Biochar Influence upon Rice (*Oryza sativa* L.) Yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. *Environmental Science & Technology*, *47*(15), 8624–8632. https://doi.org/10.1021/es400554x

Kim, H.-S., Kim, K.-R., Kim, H.-J., Yoon, J.-H., Yang, J. E., Ok, Y. S., Owens, G., & Kim, K.-H. (2015). Effect of biochar on heavy metal immobilization and uptake by lettuce (*Lactuca sativa* L.) in agricultural soil. *Environmental Earth Sciences*, *74*(2), 1249–1259. https://doi.org/10.1007/s12665-015-4116-1

Knicker, H. (2010). “Black nitrogen” – an important fraction in determining the recalcitrance of charcoal. *Organic Geochemistry*, *41*(9), 947–950. https://doi. org /10.1016/j.orggeochem.2010.04.007

Kranz, C. N., McLaughlin, R. A., Johnson, A., Miller, G., & Heitman, J. L. (2020). The effects of compost incorporation on soil physical properties in urban soils – A concise review. *Journal of Environmental Management*, *261*, 110209. https://doi.org/10.1016/j.jenvman.2020.110209

Kukal, S. S. (2004). Water-saving irrigation scheduling to rice (Oryza sativa) in indo-gangetic plains of India. In G. Huang & L. S. Pereira (Eds.), *Land and water management: decision tools and practices* (pp. 83–87). China Agricultural University.

Laghari, M., Mirjat, M. S., Hu, Z., Fazal, S., Xiao, B., Hu, M., Chen, Z., & Guo, D. (2015). Effects of biochar application rate on sandy desert soil properties and sorghum growth. *Catena*, *135*, 313–320. https://doi.org/10.1016/j.catena.2015.08.013

Lai, L., Ismail, M. R., Muharam, F. M., Yusof, M. M., Ismail, R., & Jaafar, N. M. (2017). Effects of Rice Straw Biochar and Nitrogen Fertilizer on Rice Growth and Yield. *Asian Journal of Crop Science*, *9*(4), 159–166. https://doi.org/10.3923/ajcs.2017.159.166

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, *158*(3–4), 443–449. https://doi.org/10.1016j./geoderma. 2010.05.013

Lambers, H., Chapin III, S. F., & Pons, T. L. (2008). *Plant Physiological Ecology* (Second). Springer.

Lampayan, R. M., Rejesus, R. M., Singleton, G. R., & Bouman, B. A. M. (2015). Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, *170*, 95–108. https://doi org/.10.1016/j.fcr.2014.10.013

Lashermes, G., Houot, S., & Barriuso, E. (2010). Sorption and mineralization of organic pollutants during different stages of composting. *Chemosphere*, *79*(4), 455–462. https://doi.org/10.1016/j.chemosphere.2010.01.041

Lee, Y. L., Ahmed, O. H., Wahid, S. A., & AB Aziz, Z. F. (2021). Biochar Tablets with and without embedded fertilizer on the soil chemical characteristics and nutrient use efficiency of *Zea mays*. *Sustainability*, *13*(9), 4878. https://doi.org/10.3390/su13094878

Lehmann, J. (2007a). A handful of carbon. *Nature*, *447*(7141), 143–144. https://doi.org/10.1038/447143a

Lehmann, J. (2007b). Bio-energy in the black. *Frontiers in Ecology and the Environment*, *5*(7), 381–387. https://doi.org/https://doi.org/10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2

Lehmann, J., & Stephen, J. (2015). *Biochar for environmental management* (J. Lehmann & J. Stephen (eds.); 2nd ed.). Routledge.

Li, Mengying, & Cai, L. (2021). Biochar and arbuscular mycorrhizal fungi play different roles in enabling maize to uptake phosphorus. *Sustainability*, *13*(6),

3244. https://doi.org/10.3390/su13063244

Li, Ming, Liu, M., Li, Z., Jiang, C., & Wu, M. (2016). Soil N transformation and microbial community structure as affected by adding biochar to a paddy soil of subtropical China. *Journal of Integrative Agriculture*, *15*(1), 209–219. https://doi.org/10.1016/S2095-3119(15)61136-4

Li, Zichuan, Song, Z., Singh, B. P., & Wang, H. (2019). The impact of crop residue biochars on silicon and nutrient cycles in croplands. *Science of The Total Environment*, *659*, 673–680. https://doi.org/10.1016/j.scitotenv.2018.12.381

Li, Zimin, & Delvaux, B. (2019). Phytolith-rich biochar: A potential Si fertilizer in desilicated soils. *GCB Bioenergy*, *11*(11), 1264–1282. https://doi.org/10.1111/gcbb.12635

Liang, B., Lehmann, J., Solomon, D., Sohi, S., Thies, J. E., Skjemstad, J. O., Luizão, F. J., Engelhard, M. H., Neves, E. G., & Wirick, S. (2008). Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta*, *72*(24), 6069–6078. https://doi.org/10.1016/j.gca.2008.09.028

Liang, K., Zhong, X., Huang, N., Lampayan, R. M., Pan, J., Tian, K., & Liu, Y. (2016). Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. *Agricultural Water Management*, *163*, 319–331. https://doi.org/10.1016/j.agwat.2015.10.015

Linquist, B. A., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., da Rosa, E. F. F., & van Kessel, C. (2015). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, *21*(1), 407–417. https://doi.org/10.1111/gcb.12701

Liu, P., Ptacek, C. J., Blowes, D. W., Berti, W. R., & Landis, R. C. (2015). Aqueous leaching of organic acids and dissolved organic carbon from various biochars prepared at different temperatures. *Journal of Environmental Quality*, *44*(2), 684–695. https://doi.org/10.2134/jeq2014.08.0341

Liu, S., Tang, W., Yang, F., Meng, J., Chen, W., & Li, X. (2017). Influence of biochar application on potassium-solubilizing Bacillus mucilaginosus as potential biofertilizer. *Preparative Biochemistry & Biotechnology*, *47*(1), 32–37. https://doi.org/10.1080/10826068.2016.1155062

Liu, X. H., Han, F. ., & Zhang, X. C. (2012). Effect of biochar on soil aggregates in the loess plateau: results from incubation experiments. *International Journal of Agriculture and Biology*, *14*(6), 975–979.

Liu, Yi, Wan, K., Tao, Y., Li, Z., Zhang, G., Li, S., & Chen, F. (2013). Carbon dioxide flux from rice paddy soils in central China: Effects of intermittent flooding and draining cycles. *PLoS ONE*, *8*(2), e56562. https://doi.org/10.1371/journal.pone.0056562

Liu, Yuxue, Lonappan, L., Brar, S. K., & Yang, S. (2018). Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: A review. *Science of The Total Environment*, *645*, 60–70. https://doi.org/10.1016/j.scitotenv.2018.07.099

Liu, Yuxue, Lu, H., Yang, S., & Wang, Y. (2016). Impacts of biochar addition on rice yield and soil properties in a cold waterlogged paddy for two crop seasons. *Field Crops Research*, *191*, 161–167. https://doi.org/10.1016/j.fcr.2016.03.003

Liu, Z., Cheng, X., Sun, D., Meng, J., & Chen, W. (2017). Maize stover biochar increases urea (15 N isotope) retention in soils but does not promote its acquisition by plants during a 4-year pot experiment. *Chilean Journal of Agricultural Research*, *77*(4), 382–389. https://doi.org/10.4067/S0718-58392017000400382

Liu, Z., He, T., Cao, T., Yang, T., Meng, J., & Chen, W. (2017). Effects of biochar application on nitrogen leaching, ammonia volatilization and nitrogen use efficiency in two distinct soils. *Journal of Soil Science and Plant Nutrition*, *ahead*, 0–0. https://doi.org/10.4067/S0718-95162017005000037

Liu, Zuolin, Dugan, B., Masiello, C. A., Barnes, R. T., Gallagher, M. E., & Gonnermann, H. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. *Journal of Hydrology*, *533*, 461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007

Livsey, J., Kätterer, T., Vico, G., Lyon, S. W., Lindborg, R., Scaini, A., Da, C. T., & Manzoni, S. (2019). Do alternative irrigation strategies for rice cultivation decrease water footprints at the cost of long-term soil health? *Environmental Research Letters*, *14*(7), 074011. https://doi.org/10.1088/1748-9326/ab2108

Luo, Y., Jiao, Y., Zhao, X., Li, G., Zhao, L., & Meng, H. (2014). Improvement to maize growth caused by biochars derived from six feedstocks prepared at three different temperatures. *Journal of Integrative Agriculture*, *13*(3), 533–540. https://doi.org/10.1016/S2095-3119(13)60709-1

Lv, D., Xu, M., Liu, X., Zhan, Z., Li, Z., & Yao, H. (2010). Effect of cellulose, lignin, alkali and alkaline earth metallic species on biomass pyrolysis and gasification. *Fuel Processing Technology*, *91*(8), 903–909. https://doi.org/10.1016/j.fuproc.2009.09.014

Madiba, O. F., Solaiman, Z. M., Carson, J. K., & Murphy, D. V. (2016). Biochar increases availability and uptake of phosphorus to wheat under leaching conditions. *Biology and Fertility of Soils*, *52*(4), 439–446. https://doi. org/10.1007/s00374-016-1099-3

Maheshwari, D.K. (2014). *Composting for Sustainable Agriculture* (Dinesh K. Maheshwari (ed.); Vol. 3). Springer International Publishing. https://doi.org/10.1007/978-3-319-08004-8

Maikol, N., Haruna, A. O., Maru, A., Asap, A., & Medin, S. (2021). Utilization of urea and chicken litter biochar to improve rice production. *Scientific Reports*, *11*(1), 9955. https://doi.org/10.1038/s41598-021-89332-y

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2012). Nutrient leaching in a colombian savanna oxisol amended with biochar. *Journal of Environmental Quality*, *41*(4), 1076–1086. https://doi.org/10.2134/jeq20 11.0128

Manickam, T., Cornelissen, G., Bachmann, R., Ibrahim, I., Mulder, J., & Hale, S. (2015). Biochar Application in malaysian sandy and acid sulfate soils: soil amelioration effects and improved crop production over two cropping seasons. *Sustainability*, *7*(12), 16756–16770. https://doi.org/10.3390/su71215842

MARDI. (2016). *Padi MARDI Siraj 297 – Varieti Padi Berhasil Tinggi*. Malaysian Agricultural Research and Development Institute. https://blogmardi.wordpress.com/2016/02/04/padi-mardi-siraj-297-varieti-padi-berhasil-tinggi/

Marsi, M., & Sabaruddin, S. (2011). Phosphate adsorption capacity and organic matter effect on dynamics of P availability in upland ultisol and lowland inceptisol. *Journal of Tropical Soils*, *16*(2), 107–114.

Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., & Cornelissen, G. (2014). Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science*, *177*(5), 681–695. https://doi.org/10.1002/jpln.201300590

McGarity, J. W., & Myers, M. G. (1967). A survey of urease activity in soils of Northern New South Wales. *Plant and Soil*, *27*(2), 217–238. https://doi.org/10.1007/BF01373391

McKenzie, B. M., Tisdall, J. M., & Vance, W. H. (2011). Soil Physical Quality BT - Encyclopedia of Agrophysics. In J. Gliński, J. Horabik, & J. Lipiec (Eds.), *Encyclopedia of Agrophysics* (pp. 770–777). Springer Netherlands. https://doi.org/10.1007/978-90-481-3585-1_153

McLennon, E., Dari, B., Jha, G., Sihi, D., & Kankarla, V. (2021). Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. *Agronomy Journal*. https://doi.org /10.1002/agj2.20814

Mensah, A. K., & Frimpong, K. A. (2018). Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal savannah soils in Ghana. *International Journal of Agronomy*, *2018*, 1–8. https://doi.org/10.1155/2018/6837404

Miyata, A., Leuning, R., Denmead, O. T., Kim, J., & Harazono, Y. (2000). Carbon dioxide and methane fluxes from an intermittently flooded paddy field. *Agricultural and Forest Meteorology*, *102*(4), 287–303. https://doi.org/10.1016 /S0168-1923(00)00092-7

Monaco, F., Sali, G., Ben Hassen, M., Facchi, A., Romani, M., & Valè, G. (2016). Water management options for rice cultivation in a temperate area: a multi-objective model to explore economic and water saving results. *Water*, *8*(8), 336. https://doi.org/10.3390/w8080336

Mosharrof, M., Uddin, M. K., Jusop, S., Sulaiman, M. F., Shamsuzzaman, S. M., & Haque, A. N. A. (2021a). Integrated use of biochar and lime as a tool to improve maize yield and mitigate CO_2 emission: A review. *Chilean Journal of Agricultural Research*, 81(1), 109–118. https://doi.org/10.4067/S0718-58392021000100109

Mosharrof, M., Uddin, M. K., Jusop, S., Sulaiman, M. F., Shamsuzzaman, S. M., & Haque, A. N. A. (2021b). Changes in acidic soil chemical properties and carbon dioxide emission due to biochar and lime treatments. *Agriculture*, *11*(3), 219. https://doi.org/10.3390/agriculture11030219

Mosharrof, M., Uddin, M. K., Sulaiman, M. F., Mia, S., Shamsuzzaman, S. M., & Haque, A. N. A. (2021). Combined application of biochar and lime increases maize yield and accelerates carbon loss from an acidic soil. *Agronomy*, *11*(7), 1313. https://doi.org/10.3390/agronomy11071313

Moyano, F. E., Manzoni, S., & Chenu, C. (2013). Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. *Soil Biology and Biochemistry*, *59*, 72–85. https://doi.org/10.1016/j.soilbio.2013.01.002

Mukherjee, A., Zimmerman, A. R., & Harris, W. (2011). Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*, *163*(3–4), 247–255. https://doi.org/10.1016/j.geoderma.2011.04.021

Nagabovanalli Basavarajappa, P., Shruthi, Lingappa, M., G. G, K., & Goudra Mahadevappa, S. (2021). Nutrient requirement and use efficiency of rice (Oryza sativa L.) as influenced by graded levels of customized fertilizer. *Journal of Plant Nutrition*, 1–15. https://doi.org/10.1080/01904167.2021.1927081

Nanda, S., Mohanty, P., Pant, K. K., Naik, S., Kozinski, J. A., & Dalai, A. K. (2013). Characterization of North American lignocellulosic biomass and biochars in terms of their candidacy for alternate renewable fuels. *BioEnergy Research*, *6*(2), 663–677. https://doi.org/10.1007/s12155-012-9281-4

Nartey, O. D., & Zhao, B. (2014). Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: An overview. *Advances in Materials Science and Engineering*, *2014*, 1–12. https://doi.org/10.1155/2014/715398

Nelissen, V., Rütting, T., Huygens, D., Staelens, J., Ruysschaert, G., & Boeckx, P. (2012). Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil Biology and Biochemistry*, *55*, 20–27. https://doi.org/10.1016/j.soilbio.2012.05.019

Nguyen, B. T., Lehmann, J., Hockaday, W. C., Joseph, S., & Masiello, C. A. (2010). Temperature Sensitivity of black carbon decomposition and oxidation. *Environmental Science & Technology*, *44*(9), 3324–3331. https://doi.org/10.1021/es903016y

Nguyen, B. T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S. J., & Engelhard, M. H. (2008). Long-term black carbon dynamics in cultivated soil. *Biogeochemistry*, *89*(3), 295–308. https://doi.org/10.1007/s10533-008-9220-9

Nguyen, T. T. N., Wallace, H. M., Xu, C.-Y., Xu, Z., Farrar, M. B., Joseph, S., Van Zwieten, L., & Bai, S. H. (2017). Short-term effects of organo-mineral biochar and organic fertilisers on nitrogen cycling, plant photosynthesis, and nitrogen use efficiency. *Journal of Soils and Sediments*, *17*(12), 2763–2774. https://doi. org /10.1007/s11368-017-1839-5

Noordin, W. D., & Shafar, J. M. (2017). Soils under hevea in peninsular malaysia: identification and distribution of clay minerals. *Proceedings of International Rubber Conference*, 268–276.

Norton, G. J., Shafaei, M., Travis, A. J., Deacon, C. M., Danku, J., Pond, D., Cochrane, N., Lockhart, K., Salt, D., Zhang, H., Dodd, I. C., Hossain, M., Islam, M. R., & Price, A. H. (2017). Impact of alternate wetting and drying on rice physiology, grain production, and grain quality. *Field Crops Research*, *205*, 1–13. https://doi.org/10.1016/j.fcr.2017.01.016

Novak, J. M., Busscher, W. J., Watts, D. W., Amonette, J. E., Ippolito, J. A., Lima, I. M., Gaskin, J., Das, K. C., Steiner, C., Ahmedna, M., Rehrah, D., & Schomberg, H. (2012). Biochars impact on soil-moisture storage in an ultisol and two Aridisols. *Soil Science*, *177*(5), 310–320. https://doi.org/10.1097/SS.0b013e31824e5593

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., & Børresen, T. (2016). In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research*, *155*, 35–44. https://doi.org/10.1016/j.still.2015.08.002

Okuma, E., Jahan, M. S., Munemasa, S., Hossain, M. A., Muroyama, D., Islam, M. M., Ogawa, K., Watanabe-Sugimoto, M., Nakamura, Y., Shimoishi, Y., Mori, I. C., & Murata, Y. (2011). Negative regulation of abscisic acid-induced stomatal closure by glutathione in Arabidopsis. *Journal of Plant Physiology*, *168*(17), 2048–2055. https://doi.org/10.1016/j.jplph.2011.06.002

Oladele, S., Adeyemo, A., Awodun, M., Ajayi, A., & Fasina, A. (2019). Effects of biochar and nitrogen fertilizer on soil physicochemical properties, nitrogen use efficiency and upland rice (*Oryza sativa*) yield grown on an Alfisol in Southwestern Nigeria. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(3), 295–308. https://doi.org/10.1007/s40093-019-0251-0

Oladele, S. O., Adeyemo, A. J., & Awodun, M. A. (2019). Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. *Geoderma*, *336*, 1–11. https://doi.org/10. 1016/j.geoderma.2018.08.025

Oleszczuk, P., Jośko, I., Kuśmierz, M., Futa, B., Wielgosz, E., Ligęza, S., & Pranagal, J. (2014). Microbiological, biochemical and ecotoxicological evaluation of soils in the area of biochar production in relation to polycyclic aromatic hydrocarbon content. *Geoderma*, *213*, 502–511. https://doi.org/ 10.1016 /j.geoderma.2013.08.027

Oliver, V., Cochrane, N., Magnusson, J., Brachi, E., Monaco, S., Volante, A., Courtois, B., Vale, G., Price, A., & Teh, Y. A. (2019). Effects of water management and cultivar on carbon dynamics, plant productivity and biomass allocation in European rice systems. *Science of The Total Environment*, *685*, 1139–1151. https://doi.org/10.1016/j.scitotenv.2019.06.110

Oo, A. Z., Sudo, S., Inubushi, K., Chellappan, U., Yamamoto, A., Ono, K., Mano, M., Hayashida, S., Koothan, V., Osawa, T., Terao, Y., Palanisamy, J., Palanisamy, E., & Venkatachalam, R. (2018). Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. *Agronomy*, *8*(10), 202. https://doi.org/10.3390/agronomy 8100202

Opala, P. A., Okalebo, J. R., & Othieno, C. O. (2012). Effects of organic and inorganic materials on soil acidity and phosphorus availability in a soil incubation study. *ISRN Agronomy*, *2012*, 597216. https://doi.org/10.5402 /2012/597216

Ouyang, L., Tang, Q., Yu, L., & Zhang, R. (2014). Effects of amendment of different biochars on soil enzyme activities related to carbon mineralisation. *Soil Research*, *52*(7), 706. https://doi.org/10.1071/SR14075

Painter, T. J. (1998). Carbohydrate polymers in food preservation: an integrated view of the Maillard reaction with special reference to discoveries of preserved foods in Sphagnum-dominated peat bogs. *Carbohydrate Polymers*, *36*(4), 335–347. https://doi.org/10.1016/ S0144-8617(97)00258-0

Pandey, A., Mai, V. T., Vu, D. Q., Bui, T. P. L., Mai, T. L. A., Jensen, L. S., & de Neergaard, A. (2014). Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agriculture, Ecosystems & Environment*, *196*, 137–146. https://doi.org/10. 1016 /j.agee.2014.06.010

Pandis, C., Spanoudaki, A., Kyritsis, A., Pissis, P., Hernández, J. C. R., Gómez Ribelles, J. L., & Monleón Pradas, M. (2011). Water sorption characteristics of poly(2-hydroxyethyl acrylate)/silica nanocomposite hydrogels. *Journal of Polymer Science Part B: Polymer Physics*, *49*(9), 657–668. https://doi.org /10.1002/polb.22225

Panhwar, Q. A., Naher, U. A., Shamshuddin, J., Othman, R., & Ismail, M. R. (2016). Applying limestone or basalt in combination with bio-fertilizer to sustain rice production on an acid sulfate soil in Malaysia. In *Sustainability* (Vol. 8, Issue 7). https://doi.org/10.3390/su8070700

Paramananthan, S. (1987). *Field legend for soil surveys in Malaysia*. Serdang: Penerbit Universiti Pertanian Malaysia, 1987.

Pardo, G. S., Sarmah, A. K., & Orense, R. P. (2019). Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. *Géotechnique*, *69*(6), 471–480. https://doi.org/10.1680/jgeot.17.P.040

Pascual, V. J., & Wang, Y.-M. (2017). Utilizing rainfall and alternate wetting and drying irrigation for high water productivity in irrigated lowland paddy rice in southern Taiwan. *Plant Production Science*, *20*(1), 24–35. https://doi.org/10.1080/1343943X.2016.1242373

Peng, X., Ye, L. L., Wang, C. H., Zhou, H., & Sun, B. (2011). Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil and Tillage Research*, *112*(2), 159–166. https://doi.org/10.1016/j.still.2011.01.002

Pereira, E. I. P., Suddick, E. C., Mansour, I., Mukome, F. N. D., Parikh, S. J., Scow, K., & Six, J. (2015). Biochar alters nitrogen transformations but has minimal effects on nitrous oxide emissions in an organically managed lettuce mesocosm. *Biology and Fertility of Soils*, *51*(5), 573–582. https://doi.org/10.1007/s00374-015-1004-5

Purakayastha, T. J., Bera, T., Bhaduri, D., Sarkar, B., Mandal, S., Wade, P., Kumari, S., Biswas, S., Menon, M., Pathak, H., & Tsang, D. C. W. (2019). A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security. *Chemosphere*, *227*, 345–365. https://doi.org/10.1016/j.chemosphere.2019.03.170

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Srinivasa Rao, C., Sandeep, S., Rinklebe, J., Ok, Y. S., Choudhury, B. U., Wang, H., Tang, C., Wang, X., Song, Z., & Freeman II, O. W. (2019). *Chapter One - Soil organic carbon dynamics: Impact of land use changes and management practices: A review* (D. L. B. T.-A. in A. Sparks (ed.); Vol. 156, pp. 1–107). Academic Press. https://doi.org/https://doi.org/10.1016/bs.agron. 2019.02.001

Rawat, J., Saxena, J., & Sanwal, P. (2019). Biochar: A sustainable approach for improving plant growth and soil properties. In *Biochar - An imperative amendment for soil and the environment*. IntechOpen. https://doi.org /10.5772/intechopen.82151

Riaz, A., Khaliq, A., Fiaz, S., Noor, M. A., Nawaz, M. M., Mahboob, W., & Ullah, S. (2018). Weed Management in direct seeded rice grown under varying tillage systems and alternate water regimes. *Planta Daninha*, *36*. https://doi.org/10.1590/s0100-83582018360100059

Ritchie, J. T., & Adams, J. E. (1974). Field measurement of evaporation from soil shrinkage cracks. *Soil Science Society of America Journal*, *38*(1), 131–134. https://doi.org/10.2136/sssaj1974.03615995003800010040x

Rogovska, N., Laird, D. A., & Karlen, D. L. (2016). Corn and soil response to biochar application and stover harvest. *Field Crops Research*, *187*, 96–106. https://doi.org/10.1016/j.fcr.2015.12.013

Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biology and Fertility of Soils*, *43*(6), 699–708. https://doi.org/10.1007/s00374-006-0152-z

Sahrawat, K. L., Ravi Kumar, G., & Rao, J. K. (2002). Evaluation of triacid and dry ashing procedures for determining potassium, calcium, magnesium, iron, zinc, manganese, and copper in plant materials. *Communications in Soil Science and Plant Analysis*, *33*(1–2), 95–102. https://doi.org/10.1081/CSS-120002380

Saletnik, B., Zagula, G., Bajcar, M., Czernicka, M., & Puchalski, C. (2018). Biochar and biomass ash as a soil Ameliorant: The effect on selected soil properties and yield of giant miscanthus (Miscanthus x giganteus). *Energies*, *11*(10), 2535. https://doi.org/10.3390/en11102535

Schefe, C. R., Patti, A. F., Clune, T. S., & Jackson, W. R. (2008). Organic amendment addition enhances phosphate fertiliser uptake and wheat growth in an acid soil. *Soil Research*, *46*(8), 686. https://doi.org/10.1071/SR08035

Schiemenz, K., & Eichler-Löbermann, B. (2010). Biomass ashes and their phosphorus fertilizing effect on different crops. *Nutrient Cycling in Agroecosystems*, *87*(3), 471–482. https://doi.org/10.1007/s10705-010-9353-9

Schjønning, P., Lamandé, M., Berisso, F. E., Simojoki, A., Alakukku, L., & Andreasen, R. R. (2013). Gas Diffusion, non-darcy air permeability, and computed tomography images of a clay subsoil affected by compaction. *Soil Science Society of America Journal*, *77*(6), 1977–1990. https://doi.org/10.2136/sssaj2013.06.0224

Schmidt, M. W. I., & Noack, A. G. (2000). Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles*, *14*(3), 777–793. https://doi.org/10.1029/1999GB 001208

Schollenberger, C. J., & Simon, R. H. (1945). Determination of exchange capacity and exchangeable bases in soil—ammonium acetate method. *Soil Science*, *59*(1).

Sepaskhah, A. R., & Barzegar, M. (2010). Yield, water and nitrogen-use response of rice to zeolite and nitrogen fertilization in a semi-arid environment. *Agricultural*

Water Management, *98*(1), 38–44. https://doi.org/10.1016/j.agwat.2010.07.013

Shakya, A., & Agarwal, T. (2017). Poultry litter biochar: An approach towards poultry litter management– A Review. *International Journal of Current Microbiology and Applied Sciences*, *6*(10), 2657–2668. https://doi.org/10.20546/ijcmas.2017.610.314

Shariff, A., Abdullah, N., & Aziz, S. (2014). Slow pyrolysis of oil palm empty fruit bunches for biochar production and characterisation. *Journal of Physical Science*, *25*, 97–112.

Sharma, N. K., Singh, R. J., & Kumar, K. (2012). Dry matter accumulation and nutrient uptake by wheat (*Triticum aestivum* L.) under poplar (*Populus deltoides*) based agroforestry system. *ISRN Agronomy*, *2012*, 1–7. https://doi.org/10.5402/2012/359673

Shetty, R., & Prakash, N. B. (2020). Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. *Scientific Reports*, *10*(1), 12249. https://doi.org/10.1038/s41598-020-69262-x

Shi, R., Li, Ni, N., & Xu, R. (2019). Understanding the biochar's role in ameliorating soil acidity. *Journal of Integrative Agriculture*, *18*(7), 1508–1517. https://doi.org/10.1016/S2095-3119(18)62148-3

Siemens, J., & Kaupenjohann, M. (2002). Contribution of dissolved organic nitrogen to N leaching from four German agricultural soils. *Journal of Plant Nutrition and Soil Science*, *165*(6), 675–681. https://doi.org/10.1002/jpln.200290002

Simonsson, M., Hillier, S., & Öborn, I. (2009). Changes in clay minerals and potassium fixation capacity as a result of release and fixation of potassium in long-term field experiments. *Geoderma*, *151*(3–4), 109–120. https://doi.org/10.1016/j.geoderma.2009.03.018

Singh Jatav, H., Kumar Singh, S., Singh Jatav, S., D. Rajput, V., Parihar, M., Kumar Mahawer, S., Kumar Singhal, R., & Sukirtee. (2020). Importance of biochar in agriculture and its consequence. In A. A. A. and M. H. H. Abbas (Ed.), *Applications of Biochar for Environmental Safety*. IntechOpen. https://doi. org/10.5772/intechopen.93049

Sohrabi, M., Rafii, M. Y., Hanafi, M. M., Siti Nor Akmar, A., & Latif, M. A. (2012). Genetic Diversity of upland rice germplasm in malaysia based on quantitative traits. *The Scientific World Journal*, *2012*, 1–9. https://doi.org/10.1100/2012/416291

Soinne, H., Hovi, J., Tammeorg, P., & Turtola, E. (2014). Effect of biochar on phosphorus sorption and clay soil aggregate stability. *Geoderma*, *219–220*, 162–167. https://doi.org/10.1016/j.geoderma.2013.12.022

Solaiman, Z. M., & Anawar, H. M. (2015). Application of biochars for soil constraints: challenges and solutions. *Pedosphere*, *25*(5), 631–638. https://doi.org/10.1016/S1002-0160(15)30044-8

Solaiman, Z. M., Shafi, M. I., Beamont, E., & Anawar, H. M. (2020). Poultry litter biochar increases mycorrhizal colonisation, soil fertility and cucumber yield in a fertigation system on sandy soil. *Agriculture*, *10*(10), 480. https://doi.org /10.3390/agriculture10100480

Solaiman, Z., Sarcheshmehpour, M., Abbott, L., & Blackwell, P. (2010). Effect of biochar on arbuscular mycorrhizal colonisation, growth, P nutrition and leaf gas exchange of wheat and clover influenced by different water regimes. *19th World Congress of Soil Science, Soil Solutions for a Changing World*, 35–37.

Song, Y., Zou, Y., Wang, G., & Yu, X. (2017). Stimulation of nitrogen turnover due to nutrients release from aggregates affected by freeze-thaw in wetland soils. *Physics and Chemistry of the Earth, Parts A/B/C*, *97*, 3–11. https://doi.org/ 10.1016/j.pce.2016.12.005

Spokas, K. A., Novak, J. M., & Venterea, R. T. (2012). Biochar's role as an alternative N-fertilizer: ammonia capture. *Plant and Soil*, *350*(1–2), 35–42. https://doi.org/10.1007/s11104-011-0930-8

Staff, S. S. (1999). *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*. USDA-NRCS.

Steiner, C., Glaser, B., Geraldes Teixeira, W., Lehmann, J., Blum, W. E. H., & Zech, W. (2008). Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science*, *171*(6), 893–899. https://doi.org/10.1002/ jpln. 200625199

Stewart, R. D., Abou Najm, M. R., Rupp, D. E., Lane, J. W., Uribe, H. C., Arumí, J. L., & Selker, J. S. (2015). Hillslope run-off thresholds with shrink-swell clay soils. *Hydrological Processes*, *29*(4), 557–571. https://doi.org/10. 1002/hyp. 10165

Streubel, J. D., Collins, H. P., Garcia-Perez, M., Tarara, J., Granatstein, D., & Kruger, C. E. (2011). Influence of contrasting biochar types on five soils at increasing rates of application. *Soil Science Society of America Journal*, *75*(4), 1402–1413. https://doi.org/10.2136/sssaj2010.0325

Subhan, A., Khan, Q. U., Mansoor, M., & Khan, M. J. (2017). Effect of organic and inorganic fertilizer on the water use efficiency and yield attributes of wheat under heavy textured soil. *Sarhad Journal of Agriculture*, *33*(4). https://doi. org/10.17582/journal.sja/2017/33.4.582.590

Sudhir-Yadav, Humphreys, E., Li, T., Gill, G., & Kukal, S. S. (2012). Evaluation of tradeoffs in land and water productivity of dry seeded rice as affected by irrigation schedule. *Field Crops Research*, *128*, 180–190. https://doi.org/10.1016/j.fcr.2012.01.005

Sukiran, M. A., Kheang, L. S., Bakar, N. A., & May, C. Y. (2011). Production and characterization of bio-char from the pyrolysis of empty fruit bunches. *American Journal of Applied Sciences*, *8*(10), 984–988.

Suksabye, P., Pimthong, A., Dhurakit, P., Mekvichitsaeng, P., & Thiravetyan, P. (2016). Effect of biochars and microorganisms on cadmium accumulation in rice grains grown in Cd-contaminated soil. *Environmental Science and Pollution Research*, *23*(2), 962–973. https://doi.org/10.1007/s11356-015-4590-8

Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A.-M., Dallmeyer, I., & Garcia-Perez, M. (2016). Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass and Bioenergy*, *84*, 37–48. https://doi.org/10.1016/j.biombioe.2015.11.010

Sun, F., & Lu, S. (2014). Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *Journal of Plant Nutrition and Soil Science*, *177*(1), 26–33. https://doi.org/10.1002/jpln.201200639

Sun, H., Shi, W., Zhou, M., Ma, X., & Zhang, H. (2019). Effect of biochar on nitrogen use efficiency, grain yield and amino acid content of wheat cultivated on saline soil. *Plant, Soil and Environment*, *65* (No. 2), 83–89. https://doi.org/10.17221/525/2018-PSE

Sun, Z., Arthur, E., de Jonge, L. W., Elsgaard, L., & Moldrup, P. (2015). Pore structure characteristics after 2 years of biochar application to a sandy loam field. *Soil Science*, *180*(2), 41–46. https://doi.org/10.1097/SS.00000000 00000111

Tabatabai, M. A., & Bremner, J. M. (1969). Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry*, *1*(4), 301–307. https://doi.org/10.1016/0038-0717(69)90012-1

Takaya, C. A., Fletcher, L. A., Singh, S., Anyikude, K. U., & Ross, A. B. (2016). Phosphate and ammonium sorption capacity of biochar and hydrochar from different wastes. *Chemosphere*, *145*, 518–527. https://doi.org/10.1016/j.chemosphere.2015.11.052

Tan, X., Shao, D., Liu, H., Yang, F., Xiao, C., & Yang, H. (2013). Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. *Paddy and Water Environment*, *11*(1–4), 381–395. https:// doi.org/10.1007/s10333-012-0328-0

Tan, Z., Lin, C. S. K., Ji, X., & Rainey, T. J. (2017). Returning biochar to fields: A review. *Applied Soil Ecology*, *116*, 1–11. https://doi.org/10.1016/j.apsoil.2017.03.017

Teh, C. B. S., & Talib, J. B. (2006). *Soil physics analyses*. Universiti Putra Malaysia Press.

Thakur, A. K., Rath, S., Patil, D. U., & Kumar, A. (2011). Effects on rice plant morphology and physiology of water and associated management practices of the system of rice intensification and their implications for crop performance. *Paddy and Water Environment*, *9*(1), 13–24. https://doi.org/10.1007/s10333-010-0236-0

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, *19*(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3

Toriman, M. & Mokhtar, M. (2012). Irrigation: types, sources and problems in Malaysia. In T. S. Lee (Ed.), *Irrigation Systems and Practices in Challenging Environments* (pp. 361–370). InTech. https://doi.org/10.5772/29710

Tumrani, S. A., Pathan, P. A., & Suleman, B. M. (2015). Economic contribution of rice production and food security in Indonesia. *Asia Pacific Research Journal*, *33*, 63–74.

Tuong, T. P., & Bouman, B. A. M. (2003). Rice production in water-scarce environments. In R. B. and D. M. J.W. Kijne (Ed.), *Water productivity in agriculture: Limits and opportunities for improvement* (Vol. 1, pp. 13–42). CABI publishing Wallingford, UK.

Udoetok, I. A. (2012). Characterization of ash made from oil palm empty fruit bunches (oefb). *International Journal of Environmental Sciences*, *3*(1), 518–524. https://doi.org/10.6088/ijes.2012030131033

Ullah, S., Zhao, Q., Wu, K., Ali, I., Liang, H., Iqbal, A., Wei, S., Cheng, F., Ahmad, S., Jiang, L., Gillani, S. W., Amanullah, Anwar, S., & Khan, Z. (2021). Biochar application to rice with 15N-labelled fertilizers, enhanced leaf nitrogen concentration and assimilation by improving morpho-physiological traits and soil quality. *Saudi Journal of Biological Sciences*, *28*(6), 3399–3413. https://doi.org/10.1016/j.sjbs.2021.03.003

Vaghefi, N., Shamsudin, M. N., Makmom, A., & Bagheri, M. (2010). The economic impacts of climate change on the rice production in Malaysia. *International Journal of Agricultural Research*, *6*(1), 67–74. https://doi.org/10.3923/ijar.2011.67.74

Vassilev, S. V., Baxter, D., Andersen, L. K., Vassileva, C. G., & Morgan, T. J. (2012). An overview of the organic and inorganic phase composition of biomass. *Fuel*, *94*, 1–33. https://doi.org/10.1016/j.fuel.2011.09.030

Verheijen, F., Jeffery, S., Bastos, A. C., Van Der Velde, M., & Diafas, I. (2010). Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions. In *Environment* (Vol. 8, Issue 4). https:

//doi.org/10.2788/472

Wander, M. M., Traina, S. J., Stinner, B. R., & Peters, S. E. (1994). Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal*, *58*(4), 1130–1139. https://doi.org/10.2136/sssaj1994.03615995005800040018x

Wang, D. J., Liu, Q., Lin, J. H., & Sun, R. J. (2004). Optimum nitrogen use and reduced nitrogen loss for production of rice and wheat in the Yangtse Delta region. *Environmental Geochemistry and Health*, *26*(2), 221–227. https://doi.org/10.1023/B:EGAH.0000039584.35434.e0

Wang, D., Li, C., Parikh, S. J., & Scow, K. M. (2019). Impact of biochar on water retention of two agricultural soils – A multi-scale analysis. *Geoderma*, *340*, 185–191. https://doi.org/10.1016/j.geoderma.2019.01.012

Wang, L., Xue, C., Nie, X., Liu, Y., & Chen, F. (2018). Effects of biochar application on soil potassium dynamics and crop uptake. *Journal of Plant Nutrition and Soil Science*, *181*(5), 635–643. https://doi.org/10.1002/ jpln.201700528

Wang, S., Zheng, J., Wang, Y., Yang, Q., Chen, T., Chen, Y., Chi, D., Xia, G., Siddique, K. H. M., & Wang, T. (2021). Photosynthesis, chlorophyll fluorescence, and yield of peanut in response to biochar application. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.650432

Wang, T., Camps-Arbestain, M., & Hedley, M. (2014). The fate of phosphorus of ash-rich biochars in a soil-plant system. *Plant and Soil*, *375*(1–2), 61–74. https://doi.org/10.1007/s11104-013-1938-z

Wang, Y., & Liu, R. (2018). Improvement of acidic soil properties by biochar from fast pyrolysis. *Environmental Progress & Sustainable Energy*, *37*(5), 1743–1749. https://doi.org/10.1002/ep.12825

Wang, Y., Yin, R., & Liu, R. (2014). Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. *Journal of Analytical and Applied Pyrolysis*, *110*, 375–381. https://doi.org/10.1016/j.jaap.2014.10.006

Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil–concepts and mechanisms. *Plant and Soil*, *300*(1–2), 9–20. https://doi.org/ 10.1007/s11104-007-9391-5

Win, K. T., Okazaki, K., Ookawa, T., Yokoyama, T., & Ohwaki, Y. (2019). Influence of rice-husk biochar and Bacillus pumilus strain TUAT-1 on yield, biomass production, and nutrient uptake in two forage rice genotypes. *PLOS ONE*, *14*(7), e0220236. https://doi.org/10.1371/journal.pone.0220236

Wong, J. T. F., Chen, Z., Wong, A. Y. Y., Ng, C. W. W., & Wong, M. H. (2018). Effects of biochar on hydraulic conductivity of compacted kaolin clay. *Environmental Pollution*, *234*, 468–472. https://doi.org/10.1016/j.envpol.2017.

11.079

Wu, X. H., Wang, W., Yin, C. M., Hou, H. J., Xie, K. J., & Xie, X. L. (2017). Water consumption, grain yield, and water productivity in response to field water management in double rice systems in China. *PLOS ONE*, *12*(12), e0189280. https://doi.org/10.1371/journal.pone.0189280

Xia, H., Riaz, M., Zhang, M., Liu, B., El-Desouki, Z., & Jiang, C. (2020). Biochar increases nitrogen use efficiency of maize by relieving aluminum toxicity and improving soil quality in acidic soil. *Ecotoxicology and Environmental Safety*, *196*, 110531. https://doi.org/10.1016/j.ecoenv.2020.110531

Xie, Z., Xu, Y., Liu, G., Liu, Q., Zhu, J., Tu, C., Amonette, J. E., Cadisch, G., Yong, J. W. H., & Hu, S. (2013). Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China. *Plant and Soil*, *370*(1–2), 527–540. https://doi.org/ 10.1007/s11104-013-1636-x

Xu, Y., Ge, J., Tian, S., Li, S., Nguy-Robertson, A. L., Zhan, M., & Cao, C. (2015). Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Science of The Total Environment*, *505*, 1043–1052. https://doi.org/10.1016/ j.scitotenv.2014.10.073

Yang, C., Yang, L., Yang, Y., & Ouyang, Z. (2004). Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. *Agricultural Water Management*, *70*(1), 67–81. https://doi.org/ 10.1016/j.agwat.2004.05.003

Yang, F., Zhao, L., Gao, B., Xu, X., & Cao, X. (2016). The interfacial behavior between biochar and soil minerals and its effect on biochar stability. *Environmental Science & Technology*, *50*(5), 2264–2271. https://doi.org/ 10.1021 /acs.est.5b03656

Yang, J., Huang, D., Duan, H., Tan, G., & Zhang, J. (2009). Alternate wetting and moderate soil drying increases grain yield and reduces cadmium accumulation in rice grains. *Journal of the Science of Food and Agriculture*, *89*(10), 1728–1736. https://doi.org/10.1002/jsfa.3648

Yang, S., Chen, X., Jiang, Z., Ding, J., Sun, X., & Xu, J. (2020). Effects of biochar application on soil organic carbon composition and enzyme activity in paddy soil under water-saving irrigation. *International Journal of Environmental Research and Public Health*, *17*(1), 333. https://doi.org/10.3390/ijerph17010333

Yang, S., Peng, S., Xu, J., He, Y., & Wang, Y. (2015). Effects of water saving irrigation and controlled release nitrogen fertilizer managements on nitrogen losses from paddy fields. *Paddy and Water Environment*, *13*(1), 71–80. https: //doi. org/10.1007/s10333-013-0408-9

Yao, F., Huang, J., Cui, K., Nie, L., Xiang, J., Liu, X., Wu, W., Chen, M., & Peng, S. (2012). Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crops Research*, *126*, 16–22. https://doi.org/10.1016/j.fcr.2011.09.018

Yao, Y., Gao, B., Zhang, M., Inyang, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere*, *89*(11), 1467–1471. https://doi.org/10.1016/j.chemosphere.2012.06.002

Yu, X., Pan, L., Ying, G., & Kookana, R. S. (2010). Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars. *Journal of Environmental Sciences*, *22*(4), 615–620. https://doi.org/10.1016/S1001-0742(09)60153-4

Yu, X. Y., Mu, C. L., Gu, C., Liu, C., & Liu, X. J. (2011). Impact of woodchip biochar amendment on the sorption and dissipation of pesticide acetamiprid in agricultural soils. *Chemosphere*, *85*(8), 1284–1289. https://doi.org/10.1016/J.Chemosphere.2011.07.031

Yuan, H., Lu, T., Wang, Y., Chen, Y., & Lei, T. (2016). Sewage sludge biochar: Nutrient composition and its effect on the leaching of soil nutrients. *Geoderma*, *267*, 17–23. https://doi.org/10.1016/j.geoderma.2015.12.020

Yuan, J.-H., & Xu, R.-K. (2012). Effects of biochars generated from crop residues on chemical properties of acid soils from tropical and subtropical China. *Soil Research*, *50*(7), 570. https://doi.org/10.1071/SR12118

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Han, X., & Yu, X. (2012). Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. *Field Crops Research*, *127*, 153–160. https://doi.org/10.1016/j.fcr.2011.11.020

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., & Crowley, D. (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems & Environment*, *139*(4), 469–475. https://doi.org/10.1016/j.agee.2010.09.003

Zhang, D., Pan, G., Wu, G., Kibue, G. W., Li, L., Zhang, X., Zheng, J., Zheng, J., Cheng, K., Joseph, S., & Liu, X. (2016). Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. *Chemosphere*, *142*, 106–113. https://doi.org/10.1016/j.chemosphere.2015.04.088

Zhang, H., Voroney, R. P., & Price, G. W. (2015). Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biology and Biochemistry*, *83*, 19–28. https://doi..

org/10.1016/j.soilbio.2015.01.006

Zhang, Hao, Xue, Y., Wang, Z., Yang, J., & Zhang, J. (2009). An Alternate Wetting and Moderate Soil Drying Regime Improves Root and Shoot Growth in Rice. *Crop Science*, *49*(6), 2246–2260. https://doi.org/10.2135/cropsci2009.02.0099

Zhang, Q., Du, Z., Lou, Y., & He, X. (2015). A one-year short-term biochar application improved carbon accumulation in large macroaggregate fractions. *Catena*, *127*, 26–31. https://doi.org/10.1016/j.catena.2014.12.009

Zhang, Yunbo, Tang, Q., Peng, S., Xing, D., Qin, J., Laza, R. C., & Punzalan, B. R. (2012). Water use efficiency and physiological response of rice cultivars under alternate wetting and drying conditions. *The Scientific World Journal*, *2012*, 1–10. https://doi.org/10.1100/2012/287907

Zhao, B., Chen, J., Zhang, J., & Qin, S. (2010). Soil microbial biomass and activity response to repeated drying–rewetting cycles along a soil fertility gradient modified by long-term fertilization management practices. *Geoderma*, *160*(2), 218–224. https://doi.org/10.1016/j.geoderma.2010.09.024

Zheng, Y., Han, X., Li, Y., Liu, S., Ji, J., & Tong, Y. (2020). Effects of mixed controlled release nitrogen fertilizer with rice straw biochar on rice yield and nitrogen balance in Northeast China. *Scientific Reports*, *10*(1), 9452. https://doi.org/10.1038/s41598-020-66300-6

Zimmerman, A. R., Gao, B., & Ahn, M.-Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, *43*(6), 1169–1179. https://doi.org/10.1016/j. soilbio .2011.02.005