Evaluating Impacts of Water Stress on Rice Biomass Composition, Feedstock Availability and Bioenergy Production Potential

Nurda Hussain

A Thesis Submitted in Fulfillment of the Requirements for the

Degree of Master of Engineering in Energy Technology

Prince of Songkla University

2022

Evaluating Impacts of Water Stress on Rice Biomass Composition, Feedstock Availability and Bioenergy Production Potential

Nurda Hussain

A Thesis Submitted in Fulfillment of the Requirements for the

Degree of Master of Engineering in Energy Technology

Prince of Songkla University

2022

Thesis Title	Evaluating Impacts of Water Stress on Rice Biomass Composition, Feedstock Availability and Bioenergy Production Potential
Author	Mrs. Nurda Hussain
Major Program	Energy Technology

Major Advisor	**Examining Committee:**
....	....Chairperson
(Asst. Prof. Dr. Juntakan Taweekun)	(Dr. Muhammad Saifullah bin Abu Bakr)
	.... Committee
Co-advisors:	(Asst. Prof. Dr. Juntakan Taweekun)
....	.... Committee
(Asst. Prof. Dr. Saowapa Duangpan)	(Asst. Prof. Dr. Saowapa Duangpan)
....	.... Committee
(Assoc. Prof. Dr. Mukhtar Ahmed)	(Dr. Kittinan Maliwan)
	.... Committee
	(Dr. Thanansak Theppaya)

The Graduate School, Prince of Songkla University, has approved this thesis as fulfillment of the requirements for the Master of Engineering Degree in Energy Technology

....

(Prof. Dr. Damrongsak Faroongsarng)

Dean of Graduate School

This is to certify that the work here submitted is the result of the candidate's own investigations. Due acknowledgement has been made of any assistance received.

....Signature
(Asst. Prof. Dr. Juntakan Taweekun)
Major Advisor

....Signature
(Mrs. Nurda Hussain)
Candidate

I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

....Signature

(Mrs. Nurda Hussain)

Candidate

Thesis Title	Evaluating Impacts of Water Stress on Rice Biomass Composition, Feedstock Availability and Bioenergy Production Potential
Author	Mrs. Nurda Hussain
Major Program	Energy Technology
Academic Year	2021

ABSTRACT

Bioenergy production from rice biomass feedstock is considered as one of the potential clean energy resources and several small biomass−based powerplants has been established in rice growing areas in addition to use of rice biomass as supplementary feedstock. However, rice biomass production is significantly affected due to various factors including climatic factors, shift in rice production systems, choice of cultivars at large scale cultivation, variability in biomass production potential and water stress occurrence which results in declined biomass availability and quality. Water stress is a critical aspect which influence the rice biomass productivity and quality the most, therefore, the impacts of water stress were evaluated on six Thai rice cultivars for their biomass quality, production, and bioenergy potential. Rice cultivars were experimented in field under well−watered (WW) and water stress (WS) treatments. Data for days to maturity of rice cultivars and rice biomass contributing parameters including stem height, stem numbers and biomass yield was collected at harvest. Proximate and lignocellulosic contents of rice biomass samples were determined for biomass composition analysis. Results showed that water stress negatively affected the crop production performance which resulted in 11−41% decline in biomass yield. Cultivar stability assessment for stable biomass production indicated that cultivars Hom Pathum and Dum Ja demonstrated comparatively smaller reductions by 11% in their biomass yield production under water stress. Statistical comparison for proximate contents showed significant negative affect which influenced biomass quality as the ash contents of cultivars Hom Chan, Dum Ja and RD−15 were raised by 4−29% under water stress. Lignocellulosic evaluation revealed, an increase in lignin contents of cultivars Hom Nang Kaew, Hom Pathum, Dum Ja and RD−15 ranging from 7 to 39%. Decline in biomass production under water stress caused a 10−42% reduction in bioenergy potential of Thai rice cultivars. Results demonstrated that cultivation of stress prone rice cultivars or farmer's choice to grow specific cultivars and incidence of water stress during rice crop growth period will reduce biomass production potential, biomass feedstock availability to biomass−based powerplants and will affect powerplant's energy conversion efficiency leading to declined bioenergy production.

Keywords: Rice, Water stress, Biomass, Bioenergy, Proximate contents, Lignocellulosic properties, Correlation

Acknowledgements

All the admires and thanks are for **ALMIGHTY GOD** (The Most Merciful, and The Most Beneficent), Who is entire source of all knowledge and wisdom endowed to mankind and Who bestowed me potential and abilities for the successful completion of this imperative task. I pay my humble gratitude from the core of my heart to **Holy Prophet MUHAMMAD** (Peace Be upon Him), Who is forever a model of guidance and minaret of knowledge for humanity.

I would like to acknowledge Faculty of Engineering Prince of Songkla University for providing scholarship award for master's degree and Graduate School, Prince of Songkla University for granting thesis research funding for topics on community problem solving. I deem it my utmost pleasure to avail an opportunity to express my heartiest gratitude and deep sense of obligation to a very hard working and personalized women, my honorable supervisor, **Asst. Prof. Dr. Juntakan Taweekun**, for her kind behavior, generous transfer of knowledge, and enlightened supervision during the whole study period.

I am deeply grateful to my co−advisors **Asst. Prof. Dr. Saowapa Duangpan** and **Assoc. Prof. Dr. Mukhtar Ahmed,** with their enthusiasm, inspiration, and great efforts to explain things clearly and simply which helped to make this research interesting for me. I am very thankful to my husband **Tajamul Hussain** for great moral support and help in collecting data and field work. I offer affectionate regards to all family members who always remained with me in all circumstances and provided me timely back up and moral support.

Nurda Hussain

CONTENTS

List of Tables

List of Figures

Chapter 1

Introduction

Energy is important to social and sustainable economic development and improved quality of life. Fossil fuels consumption for energy have caused significant threats to health, ecosystem, and environment. Consequently, alternative, and renewable energy sources provide an opportunity to replace fossil fuels and obtain safe and cost‒efficient energy. Renewable energy is mostly obtained from natural resources *i.e.*, rain, wind, sunlight, tides or waves, geothermal heat, and biomass (Frankl et al., 2013; Ellabban et al., 2014). Renewable energy resources provide about 23.7% of total world's energy requirements (REN21, 2016) which include hydropower, wind energy, solar energy, biofuels, and biomass energy. In the most of developed and developing economies renewable or alternative energy offers energy security with reduced environmental impacts and enhanced economic growth and developments. Renewable resources including solar, wind, thermal, biomass and hydrogen perform a crucial role in the world's future, and they are utilized for heating purposes, electrical energy, and transportations (Khalil et al., 2010). Renewable resources for heating including cooking as well as water heating contributed 75% of whole energy consumption in the year 2010 while biomass contributed about 96% of it (Frankl et al., 2013). Biomass is currently considered as the largest renewable energy resource and has particular properties in comparison to the other renewable technologies and processes (Ladanai and Vinterbäck, 2009; Saidur et al., 2011). It is a multipurpose energy resource which generates electricity, uses for heat generation and biofuel production, furthermore, conversion of biomass into energy can revolutionize waste materials, alleviate environmental impacts caused by waste dumping and waste management, and decrease the mass as well as volume of the wastes (Kalt and Kranzl, 2011). Subsequently, it can also contribute to the future fuel supply trends and established of biomass−based power plants.

Renewable energy is being considered by numerous countries in the world because of its advantages. It has been used in Thailand as well in different form such as heat, electricity and biofuel or bioenergy. Approximately 13.8% or 11051 kilotons of oil equivalent (ktoe) of renewable energy of total energy 79929 ktoe was used in 2016 which was 9.7% more than last year based on a Report published by the Department of Alternative Energy Development and Efficiency of Ministry of Energy (DEDE, 2016). Based on report, major use of renewable energy was heat of 7183 ktoe, electricity of 2121 ktoe and biofuels about 1746 ktoe at share about 65 %, 19.2%, and 15.8% respectively. While biomass had the greatest percentage of 90.6% in heat production following biogas, the municipal wastes and by the solar energy which contributed around 8.3%, 1% and 0.1%, correspondingly. Major feedstock of biomasses was agricultural residue which generated approximately 15701 ktoe including agricultural waste around 8274 ktoe, bagasse’s around 66432 ktoe and 995 ktoe of rice husk. Industries included agro industries including sugar, rice, and palm oil industries. 2904 ktoe of heat and 5370 ktoe of power was produced by agricultural wastes. 3248 ktoe of heat and 3184 ktoe of power were produced by bagasse when it was used as fuel and 193 ktoe of heat and 802 ktoe of power were produced by rice husk.

Thailand is well organized and one of first ranked exporters of agricultural products, food and biomass which also includes multiple by−products from agricultural processes and post−harvest residues including bagasse, coconut shell and corn cob making them available for substitute energy resources (Utistham et al., 2007). Agricultural residue including rice straw and husk and corn cob have shown statistically a great potential in Thailand. Reason is the frequency of rice plantations in different regions of country. According to Cheewaphongphan and Garivait (2013), average planting frequency of rice plantation in country is 1.0 round per year but in central part it is 2−2.5 rounds per year including plantation of photosensitive and non−photosensitive rice cultivars. Total rice harvesting area in Thailand in 2015 was 9.49 million hectares (Mha) including 8.46 Mha and 1.03 Mha for major and minor rice production fields respectively (Office of Agricultural Economics OAE, 2015). According to a report of Rice Department of Thailand (Rice Department, 2017), there are approximately 116 cultivars of rice in Thailand. These cultivars are categorized into two major categories including photosensitive and non−photosensitive cultivars. Photosensitive cultivars flower and produce when the daylength is less than 12 hours and farmers prefer to plant these cultivars in month of November while non−photosensitive cultivars do not depend upon day length and can produce and cultivated round the year. Hence, the cultivation of different rice species and farmers choice to plant various cultivars and harvesting patterns also affect the rice biomass and rice residue availability in each field and location.

Water scarcity and stress occurrence is the adverse environmental condition by which crop growth and development is affected and high yield losses occurs (Lamm et al., 1994). According to Debaeke and Aboudrare, (2004), an integrative approach could be employed which is capable to account for water, crop and management to cope with water stress as one can evaluate ideal planting time to take benefit of soil water and natural rainfall, active irrigation management and other agronomic practices. Water stress causes the significant alterations in the biological processes of rice plant and reduces the overall efficiency of rice dry matter production. Most of the physiological as well as biochemical processes taking place are slowed down under water stress conditions. Leaf growth and stem elongation is affected. Light interception and transpiration rate of plants are decreased when leaf rolling is occurred. According to Lawlor and Tezara (2009), photosynthesis is the main physiological process which defines the efficiency of plant under water stress. Transpiration efficiency is the ratio among photosynthesis and transpiration (Tuong and Bouman, 2003). While the ratio among grain production or total biomass to the total amount of water transpired is known as the water use efficiency (WUE). Water use efficiency is defined by the transpiration and photosynthesis rates in plants (Tuong and Bouman, 2003). Higher WUE of plants results in higher dry matter yields. Water stress causes significant decline in yield and biomass production of a cultivar. Future climatic predictions indicate seasonal droughts in future decades. Seasonal droughts may result in significant decline in rice yield and biomass availability. Therefore, it becomes important to assess the impact of water stress on rice biomass production performance for biomass availability which will help to lay foundations of future biomass energy power plants.

Rice is considered as one of the major crops globally with wheat and maize. Existing production levels of crops for food, fiber and energy needs are overburdened due to rapid growth in population worldwide. Asia is major rice producing continent where rice is main and cheap source of carbohydrates, protein, minerals, and fiber along with the potential source of biomass feedstock for bioenergy. Rice is also one of major cereals of which straw is a potential biomass–based energy resource. Rice production is estimated to increase significantly soon to feed the rising human population resulting in higher straw biomass production as well. Rice straw biomass can be managed by soil incorporation tactics but straw incorporation into wet soil during land preparation period is linked with increased methane emissions. Rice straw and residues are usually left over in the rice fields therefore, it represents highest amounts of unutilized agricultural residues (Said et al., 2013). Nowadays, burning straw in rice fields is main practice used for removing rice straw and residues, which results in huge effect of greenhouse gases and air pollutions which subsequently impacts health of public (Wongjewboot et al., 2010). Due to these concerns use of rice biomass in renewable and alternate energy has increased significantly in recent years. Besides, agricultural production, energy resources are important for sustainable growth for economy of any country which accomplish economic growth. Use of renewable energy resources have become important to reduce the impacts of global warming and sustained fuel and energy supplies (Cuiping et al., 2004). Energy plants for bioenergy and biofuel production compete with food producing species for land and water resources. According to Stone et al. (2010) more land and water resources will be required to meet continuously increasing biofuel needs. In this scenario, crop residual biomass including rice straws and lignocellulosic biomass provide an alternative to this problem and can be converted to number of products *i.e.,* biofuels (Suzane et al., 2021). Biomass is third and one of largest energy resource worldwide following coal and petroleums (Hashem et al., 2013). Biomasses and residues are being used in small powerplants as raw material for energy generation (Varvel and Wilhelm, 2008).. Residues possess carbon neutral properties which provide an advantage over fossil energy for example they can reserve CO_2 during growing period and releasing it to environment during combustion process resulting in zero net addition of CO_2. However, most of residues and rice biomass including straws and husk are burnt in farming areas due to lack of appropriate collection from fields after grain harvest which results in energy loss and causes environmental and health concerns (Lim et al., 2012). Presently, governments worldwide have established strategic attention to practice renewable energy resources in structuring their national energy policies. In Thailand efforts are made to restructure national energy plan by boosting the shares of renewable energy resources and technologies. Biofuels, heat as well as electricity has been obtained continually through renewable energy and agricultural residues are major source for heat production in Thailand (Cheewaphongphan et al., 2018). According to the Thailand's Alternative Energy Development Plan (AEDP) of 2015, Thailand had set a goal to expand the shares of renewable energy resources and technologies to 30% in the total consumption of energy by 2036 which is almost 39,388 ktoe of energy (AEEI, 2015). AEDP's main objective is to promote renewable energy at country's full capability. Approximately 16.40−58.28 million tons of rice biomass which included rice straw and husk was estimated and it contributed major portion of available wastes from field crops. In a recent study, bioenergy potential of rice residual biomass has been estimated 807845 TJ in seven regions of Thailand (Wang et al., 2021). To achieve the goals of national plan for renewable and bioenergy, numerous small biomass−based powerplants have been set up in major rice production areas of Thailand. In these powerplants rice biomass and residues are used as main or supplementary feedstock resource to generate electricity in Thailand and its contribution is as second most important resource (Barz and Delivand, 2011).

Chapter 2

Literature Review

2.1. Impacts of water stress on rice production

Drought or water stress is the major factor in the yield reduction in rice production systems including rainfed and irrigated systems. Impact of water stress in more critical in case of rainfed rice areas, as these production systems are generally exposed to high altitude, less fertile soil, and unpredictable weather events the drought is another factor of concern in these areas. Topography and soil characteristics of these areas allow rainwater to drain out rapidly subjecting the plants to water stress conditions. As the rainfed rice mostly dependent upon rainfall, it mostly suffers the drought by unpredicted rainfalls due to climate change. Cultivation of specific improved cultivars and site for the crop plantation are major factors including the land and preparation of seedbed, production systems, planting times and planting methods, insect and disease management strategies and nutrient management from planting to maturity.

Water stress causes the significant alterations in the biological processes of rice plant and reduces the overall efficiency of rice. Efficiency of physiological and biochemical processes is lowered under water stress conditions. Reduction in the transpiration was observed as the initial response if the water stress prevails at the vegetative growth stages of rice. In addition, leaf growth and development as well as stem elongation were altered. In case of moisture contents of soil reached to 70 % of plant available water, a linear decline in productivity was observed (Lilley and Fukai, 1994). Light interception and transpiration rate decreased when leaf rolling occurred. Lilley and Fukai (1994) described that ability of young rice plants to maintain the leaf area in water stress period and efficiency to produce maximum tillers or secondary stems after the water stress or drought events are the key features of tolerance against water stress. Root system ability to extract water and the water use efficiency (WUE) of plants under water stress are the main factors for biomass and dry matter production. WUE of rice is greatly influenced by water shortage or stress intervals. Rooting depth, density and the root length are responsible for soil water extraction. Rice plants has greater root length compared to other cereals *i.e.*, maize in normal conditions however, during the stress intervals rice plants fails to sustain root growth and development affecting the efficiency to absorb water. Root distributions of rice varies from other crop plants (Kondo et al., 1999). While rice has lower potential to extract water from deep soil layers compared to other plants. Turner *et al*. (2001) and Subbarao *et al*. (1995) stated that rooting properties like root length, root density, rooting depth and root biomass significantly constitutes for water economy of rice. Deep and thick roots professionally extracted water from deep soil layers (Kavar et al., 2008) leading to higher crop water productivity and biomass production. Potential of rice to produce high biomass yield, might reduce under water stress as being sensitive to water stress. Cultivation of aerobic rice have acquired attention leading to development of the suitable cultivars those have improved production potential under aerobic systems. Rice cultivars varies in leaf growth and development either in soil or atmospheric stress. Leaf area index (LAI) mainly contributes to the water economy (Ball et al., 1994) under stress conditions. Higher water economy ultimately leads to higher biomass production.

2.2. Impacts of water stress on biomass composition and feedstock availability

Water stress leads to decline in production and continuous reduced biomass production can potentially influence the biomass feedstock availability for bioenergy production (Stone et al., 2010). Water Stress occurs at various crop growth stages due to seasonal variability in rainfalls in current scenario of climate change. Water stress or drought occurrence is serious threat to crop production for grain as well as biomass feedstock availability worldwide including Thailand. According to Office of Agricultural Economics, Thailand (Office of Agricultural Economics OAE, 2016), lowland rainfed rice system is the major component of rice production system of Thailand with 9Mha area. Rice production is vulnerable as it is dependent upon rainfall and changes in rainfall as well as reduced water availability occurs in different regions of the country. Water stress is common in Thailand when crop is at reproductive stage and crop fails to produce optimum in certain situations (Monkham et al., 2016). Water is important during all crop growth stages but reproductive stages are critical when if stress occurred will result in higher reduction in quantity as well as the quality. According to Venuprasad *et al.* (2007), rice crop is extremely sensitive and vulnerable if water stress occurred at reproductive growth stages. Water stress alters the plant biomass composition, causes substantial biomass yield losses, and reduces the quality of produce depending upon duration and intensity of stress. Biomass in terms of energy, can yield three major final products including energy for heating purpose, fuel for transport and raw material for certain chemicals (Saxena et al., 2009). While energy characteristics comprises of proximate components including moisture contents (MC), volatile matter (VM), fixed carbon (FC) and ash contents whereas, characteristics of ultimate composition includes elemental composition for carbon (C), nitrogen (N), hydrogen (H), sulfur (S) and higher heating value (HHV) (Imam and Capareda, 2012). Proximate and ultimate components are important part of biomass as the concentration of these components affects biomass quality for devolatilization, power generation and energy output. Increase in moisture contents and ash contents affects biomass quality, decreases the energy conversion efficiency and energy output, therefore low moisture contents and ash whereas high volatile matter is desired. Higher heating value is also an important component which yield to maximum energy output. Straw biomasses are completely composed of cell walls and lignified carbohydrates, structural proteins and minerals are present in these cell walls (Antongiovanni and Sargentini, 1991). Lignocellulosic properties including cellulose contents, hemicellulose contents, and lignin contents are important characteristics of biomass, and the energy conversion and pyrolysis process are affected by the behavior and concentration of these components (Van de Velden et al., 2010). Concentration of these components usually ranges 32 to 47 % for cellulose contents, 19 to 27 % for hemicellulose contents and 5 to 24 % for lignin contents (Garrote et al., 2002; Saha, 2003). Cellulose as well as hemicellulose are tightly packed layers due to outer layer of lignin. Generally, cellulose and hemicellulose are major components in straws. In biochemical conversion process, it is necessary to pretreat the rice biomass so that lignin protective layer is decomposed and cellulose as well as hemicellulose are available to start chemical and enzyme activity. Lignin is usually converted slowly at 160°C to 900 °C while cellulose and hemicellulose are decomposed rapidly at 220 °C to 315 °C and 315 °C to 400 °C respectively (Yang et al., 2007). This indicated that presence of higher lignin contents in biomass will make process more complex which require higher energy input for decomposition thus increasing the conversion cost.

Water stress affects the biomass composition for energy contents thus influence the conversion efficiency of implemented conversion process. According to Al−Hakimi *et al.* (2006), cellulose, lignin, and pectin's concentration potentially decreased whereas concentration of hemicellulose increased in soybean's shoots when grown under water stress. Hence, it becomes critical to consider the negative impacts of water stress on rice biomass composition which leads to decreased biomass quality.

2.3. Bioenergy production and potential threats

Continuous and viable biomass feedstock supply is necessary for biofuel (Emerson et al., 2014) and bioenergy production, however, water stress occurrence impact on quality and biomass production potential. According to Emerson et al. (2014), it becomes crucial to investigate the effects of water stress on crop growth as well as production and quantification of impacts of water stress on crop production is a vital element for analyzing the biomass feedstock availability. Neglecting this quantification and biomass yield estimation by cultivars and impact of water stress on production will result in reduced biomass feedstock availability to established powerplants which will not only influence energy potential but also influence input cost of energy conversion process due to changes occurred in biomass composition. Cultivar type, physiological response of a specific cultivar and the conditions of growing environment influence biomass composition and biomass yield significantly affecting the energy potential. Stable and stress tolerant cultivars with higher capability to adapt water stress conditions are recommended to be cultivated to minimize the crop production risks (Manickavelu et al., 2006) in this scenario. This is because stress tolerant cultivars exhibit a relatively stable and higher yield response under diverse range of environments ranging from irrigated to stress environments

(Anantha et al., 2016). 116 cultivars had been reported being cultivated in different rice growing areas of Thailand in a report of Rice Department (RD) of Ministry of Agriculture and Cooperatives (Rice Department, 2017). These cultivars vary in terms of their production potential and physiological characteristics. Farmers in Thailand choose to grow specific cultivars of their choice and growing experience for grain yield as they are concerned with the economic part of plant and plantation of such cultivars changes due to production level differences over years. In this case it becomes important to obtain information on cultivars production performance for biomass production potential, by cultivar type, growing site and growing conditions including sensitivity to water stress. Biomass utilization systems (Summers et al., 2003) and small biomass−based powerplants need precise biomass feedstock data and a prediction of variability and availability of biomass feedstock for their designing in specific area. Energy conversion processes are also dependent upon the characteristics, quality, and quantity of biomass feedstock available. Hence it becomes important to understand that how water stress can impact on biomass composition, biomass feedstock availability and may pose a potential threat to established small biomass−based powerplants for sustainable energy generation. Some of studies have been conducted for biomass yield estimation for establishment of biomass−based powerplants but the authors do not give attention to the cultivar types for their biomass producing potential difference under well−watered and water stressed conditions, changes predicted due to farmers choice over time and cultivars failure under water stress which can potentially lead to reduced and lower quality biomass feedstock availability. Therefore, this proposed study was carried out to observe the impacts of water stress on rice biomass productivity, biomass quality, cultivar stability and energy potential of the rice biomass feedstock of Thai rice cultivars. To the best of our knowledge, proposed research work was the first study to investigate the potential impacts of water stress and cultivar types on rice biomass composition, quality, and biomass feedstock availability to established small biomass−based powerplants.

2.4. Objectives of Research

Objectives of this research were to assess the impacts of water stress on Thai rice cultivars for biomass production under well−watered and water−stressed conditions and potential for bioenergy production. Study also aimed at analyzing variations in cultivar types, rice biomass composition quality and biomass feedstock availability for small biomass−based powerplants.

Chapter 3

Research Methodology

3.1. Plant material

Six Thai lowland rice cultivars which included Hom Nang Kaew (1), Hom Chan (2), Hom Pathum (3), Dum Ja (4), Khao Dawk Mali–105 (5) and RD–15 (6) was used for assessing the impacts of water stress on biomass production, composition, and energy potential in this study.

3.2. Methods

Methodology of study comprised of collection of data from field experiments, recording biomass, sample preparation, analysis for energy contents and computation of final energy potential. Scheme of research methodology is presented in Figure 1.

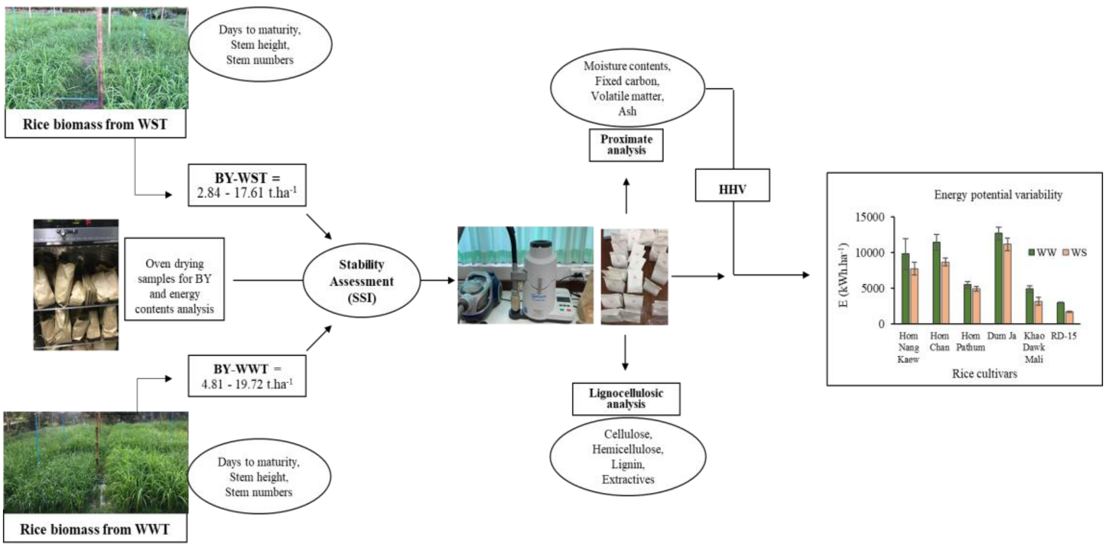

Figure 1. Scheme of research methodology.

3.2.1. Crop biomass data collection

Data for stem height (SH), stem numbers (SN) and biomass yield (BY) were collected from assessment trials conducted in the field experimental area of Faculty of Natural Resources (7°00′14.5″ N, 100°30′14.7″ E), Prince of Songkla University, Hat Yai, Songkhla Province, in Southern Thailand (Figure 2) during 2019–2020. Province of Songkhla is situated in the east of Southern Thailand and the climate of Songkhla is characterized by hot or dry season and rainy season. Mean minimum and mean maximum temperature reach 24.8 °C and 31.5 °C, respectively, with an average annual temperature of 27.9 °C and annual average rainfall of 2016.67 mm (Hussain et al., 2021a). In brief, trials were conducted using a randomized complete block design comprising three replicates and two water treatments including well–watered treatment (WWT) and water−stressed treatment (WST). Plants in WWT received supplementary irrigation throughout the growing period including rainfall; however, plants in WST received only rainfall as irrigation water after tillering stage. Each cultivar was grown in a separate plot with 4 rows of 3−m length. Plants were maintained at 25 cm while rows were distanced at 30 cm. Number of days to 50% plants maturity (DM) were recorded through counting the days from the planting date. Data collection for stem height, stem numbers and biomass yield was performed at harvest by randomly selecting three plants for each cultivar from each treatment plot (Figure 3). Plant biomass samples were first oven dried at 70 °C for various time intervals until to obtain a constant weight and obtain biomass yield on a dry weight basis.

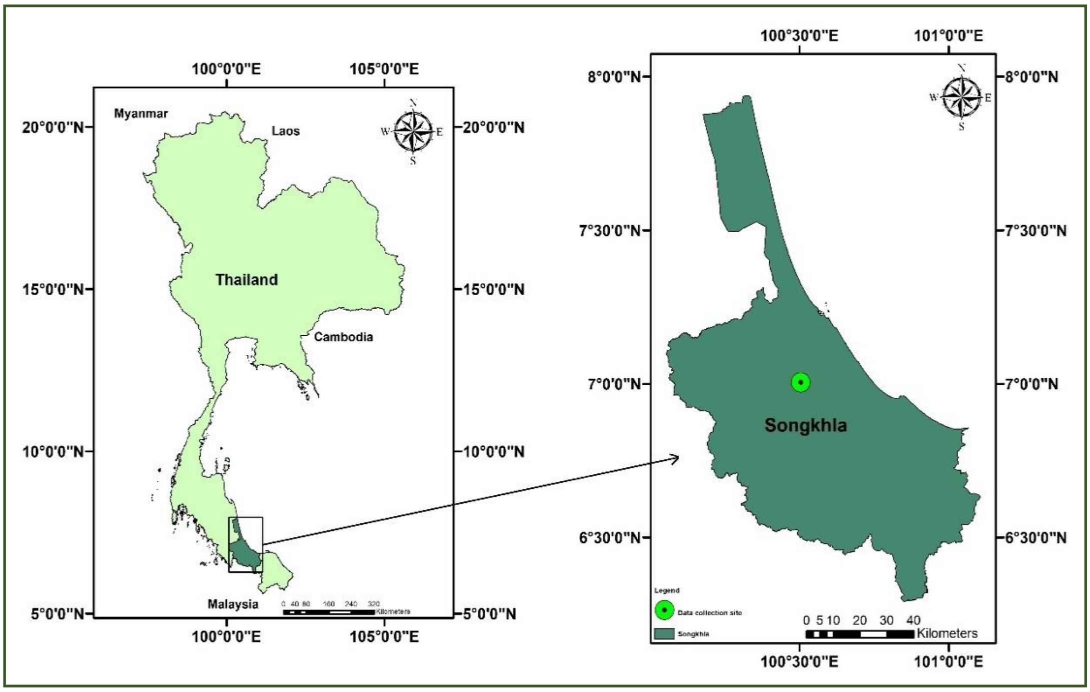

Figure 2. Data collection location at Prince of Songkla University, Thailand.

Figure 3. Data collection from well–watered treatment (WWT) and water–stressed treatment (WST).

3.2.2. Biomass sample preparation

After drying the samples in oven, plant biomass samples were ground finely into 1 mm particle size using grinder model: Retch Cyclone Mill Twister (Hussain et al., 2022) (Figure 4). The ground biomass samples were stored in sealed plastic bags until biomass composition analysis was performed.

Figure 4. Plant biomass samples drying, preparation and grinding in grinder model: Retch Cyclone Mill Twister.

3.2.3. Energy contents analysis

A composite sample from oven dried straw biomass samples from three replications was prepared for each cultivar from Well−watered and water stressed treatments. For 6 cultivars a total of 12 plant biomass samples were prepared and sent to Central Analytical Laboratory of Faculty of Natural Resources and Scientific Equipment Center, Prince of Songkla University for different following energy contents analysis.

3.2.3.1. Proximate analysis

Proximate analysis was performed in a macro thermogravimetric analyzer of model: TGA 701, LECO, USA, at the Scientific Equipment Center of Prince of Songkla University, Thailand for

- Moisture contents (MC),
- Volatile matter (VM),
- Fixed carbon (FC) and
- Ash contents of straw biomass

3.2.3.2. Lignocellulosic analysis

Lignocellulosic analysis was performed by analyzing the acid detergent fiber (ADF), and neutral detergent fiber (NDF), and acid detergent lignin (ADL) to determine the proportion of cellulose contents (1), hemicellulose contents (2), lignin contents (3) and proportion of extractives (4).

$$\text{Cellulose contents} = \text{ADF} - \text{ADL} \quad (1)$$

$$\text{Hemicellulose contents} = \text{NDF} - \text{ADF} \quad (2)$$

$$\text{Lignin contents} = \text{ADL} \quad (3)$$

$$\text{Extractives} = 100 - (\text{Cellulose} + \text{Hemicellulose} + \text{Lignin}) \quad (4)$$

3.2.3.3. Higher heating value

Higher heating value (HHV) which is also known as gross calorific value was calculated for each biomass sample by equation (5) (Lozano-García and Parras-Alcántara, 2013).

$$\text{HHV} = 0.3536\text{FC} + 0.1559\text{VM} - 0.0078\text{A} \quad (\text{MJkg}^{-1}) \quad (5)$$

where, fixed carbon is indicated by FC, volatile matter is indicated by VM and ash is indicated by A achieved from proximate analysis (Lozano-García and Parras-Alcántara, 2013).

3.2.4. Data Analysis

3.2.4.1. Statistical analysis and mean comparison

Straw biomass and biomass composition analysis data obtained from experiment and laboratory, respectively, were used separately in statistical program Statistix (Duangpan et al., 2022) to test the significance. Two−way analysis of variance (ANOVA) was accomplished for recorded days to maturity, observed stem height, counted stem numbers, and determined biomass yield from three replications with effect to applied treatments. Mean comparisons were conducted using least significant difference (LSD) and significance was consider at $p < 0.05$. ANOVA was also performed for biomass composition elements to assess the significance of results and the effect of treatments on biomass composition.

3.2.4.2. Correlation assessment

Correlation analysis was conducted to compute Pearson's correlation coefficients (Hussain et al., 2021a) for evaluated rice straw biomass contributing parameters and energy contents obtained from proximate and lignocellulosic analysis.

3.2.4.3. Stress susceptibility index (SSI)

Following the statistical results, analysis of variance and mean comparisons, straw biomass yield was taken into consideration for evaluation of stress tolerance as well as high yielding cultivars. An average yield was used to compute measure of yield stability, the water stress susceptibility index (SSI) and relative yield potential of rice cultivars (RY) by using formulae for SSI (Fischer and Maurer, 1978),

$$\text{Stress Susceptibility Index} = (1 - Yws / Yww) / D \qquad (6)$$

where,

Yws = average yield of biomass under water stress,

Yww = average yield of biomass under well–watered conditions,

D = environmental stress intensity which is 1 – (average biomass yield of all cultivars under water stress conditions / average yield of all cultivars under well–watered conditions).

Relative yield under water stress conditions was determined as the biomass yield of cultivar under water stress divided by the biomass yield of the highest biomass yielded cultivar in the studied population. Stress susceptibility index and relative yield were employed to classify stress tolerant and relatively higher biomass yielding cultivars. Cultivars having stress susceptibility index less than 1 and relative yield under stress greater than mean relative biomass yield were considered as stress tolerant and high biomass yielding cultivars respectively.

Chapter 4

Results and Discussion

4.1. Impact of water stress on rice performance

There was a highly significant alteration for days to maturity, stem height, stem numbers and biomass yield, whereas no significant difference was observed for interactions among cultivars and treatments for biomass yield (Table 1). Maximum performance for stem height, stem numbers and biomass yield were observed under well–watered condition. However, water stress significantly affected production performance of all cultivars under water stressed condition.

Table 1. Mean squares of analysis of variance for days to maturity (DM), stem height (SH), stem numbers (SN) and biomass yield (BY) of six rice cultivars.

SOV	**df**	**DM**	**SH**	**SN**	**BY**
Replication	2	5.44	69.75	917.33	0.77
Cultivars (C)	5	2224.18 ***	7699.20 ***	1996.47 ***	205.00 ***
Treatments (T)	1	498.78 ***	5088.44 ***	9604.00 ***	59.75 ***
C × T	5	14.44 ***	356.11 ***	2347.93 ***	2.05 ns
Error	22	2.23	78.02	215.24	2.06
CV %		1.04	6.42	9.67	12.88

SOV = source of variation, df = degree of freedom, *** = highly significant ($p < 0.001$), ns = non−significant.

4.1.1. Effect of water stress on rice maturity

Days to maturity ranged from 116−154 days for well−watered treatment and 120−165 days for water−stressed treatment. The difference in increase ranged 4–11 days under water stress as compared to well−watered treatment (Figure 5). Delayed maturity and increase in days to maturity is linked to delay in flowering period of rice as flowering of rice plants is delayed under water stress (Davatgar et al., 2009; Saikumar et al., 2016; Hussain et al., 2018). Delayed days to maturity of rice under water stress have been observed in numerous studies (Hussain et al., 2018, 2021b)

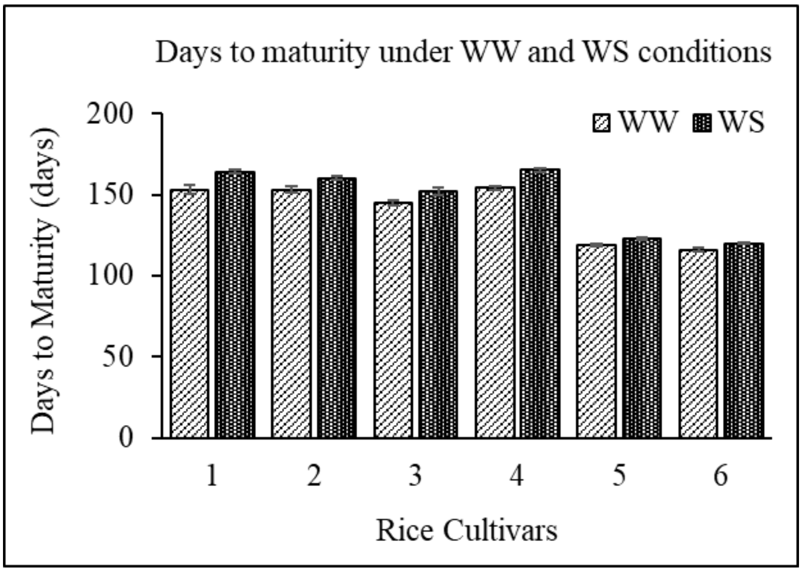

Figure 5: Effect of well−watered and water stressed treatments on days to maturity of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.1.2. Effect of water stress on rice stem height

Stem height at maturity was decreased for all cultivars under water stress (Figure 6). Stem height ranged from 101−190 cm for well−watered and 83−57 cm for water−stressed and was decreased by 3–25% under water stress as compared to well−watered treatment for tested cultivars. Davatgar et al. (2009) and Hussain et al. (2018) observed that water stress caused a significant decline in stem height of rice cultivars and the results gave been supported in recent studies (Davatgar et al., 2009; Patel et al., 2010; Anantha et al., 2016; Saikumar et al., 2016; Hussain et al., 2018; Torres and Henry, 2018). Stem height is negatively correlated with water stress. Reduction in stem height is featured as the water stress limits the cell elongation which results in internode length (Patel et al., 2010).

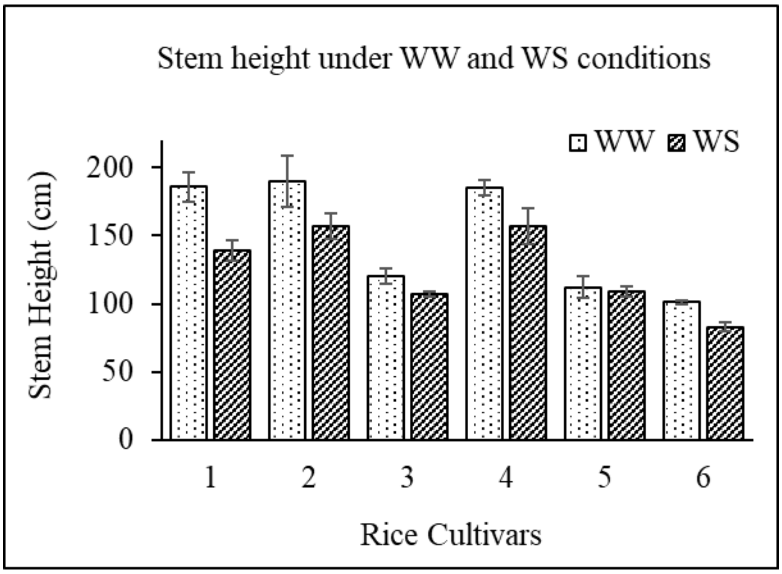

Figure 6: Effect of well−watered and water stressed treatments on stem height of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.1.3. Effect of water stress on rice stem numbers

Stem numbers per meter square (m^{-2}) were decreased for all cultivars under water stress (Figure 7). Stem numbers (m^{-2}) ranged from 127−223 stems for well−watered treatment and 118−170 stems for water stressed treatment which were decreased by 2–89% in water stressed treatment as compared to well−watered treatment. According to Zain et al. (2014), stem number of rice were reduced under increased water stress. Reduction in stem numbers and tiller mortality of rice is well reported in stress studies (Zain et al., 2014; Hussain et al., 2018, 2021b).

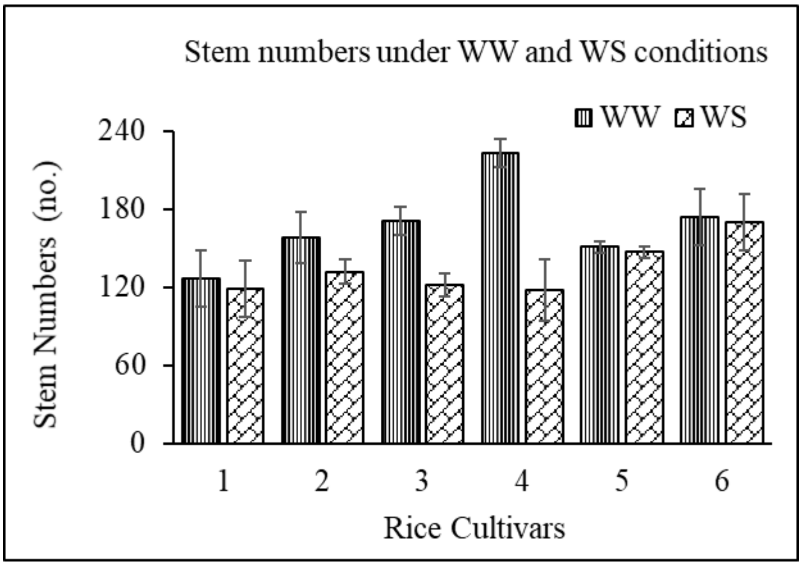

Figure 7: Effect of well−watered and water stressed treatments on stem numbers of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.1.4. Effect of water stress on rice biomass yield

Biomass yield was decreased for all cultivars under water stress, and values ranged from 4.81−19.72 $t.ha^{-1}$ for well−watered treatment and 2.84−17.61 $t.ha^{-1}$ for water stressed treatment (Figure 8). Biomass yield was reduced by 11–41% in water stressed treatment as compared to well−watered treatment (Figure 8). Rice plant is highly vulnerable to water stress (USDA, 2015; Swain et al., 2017; Ichsan et al., 2020) and biomass productivity of rice plant is significantly decreased under water stress. Increased water stress decreased the plant morphological responses and rice production in an experimental investigation conducted by Zulkarnain et al. (2009). Reduction in biomass yield of rice is witnessed and supported by recent researches (Zain et al., 2014; Hussain et al., 2018, 2021b). Biomass yield is also influenced by the performance of biomass contributing parameters in rice *i.e.*, stem height and stem number. Higher stem height and more stem numbers contribute to increase in rice plant biomass yield. Stem height had significant positive correlation with biomass yield. Knoll et al. (2021) also observed that mature stem height was highly significantly correlated with biomass yield.

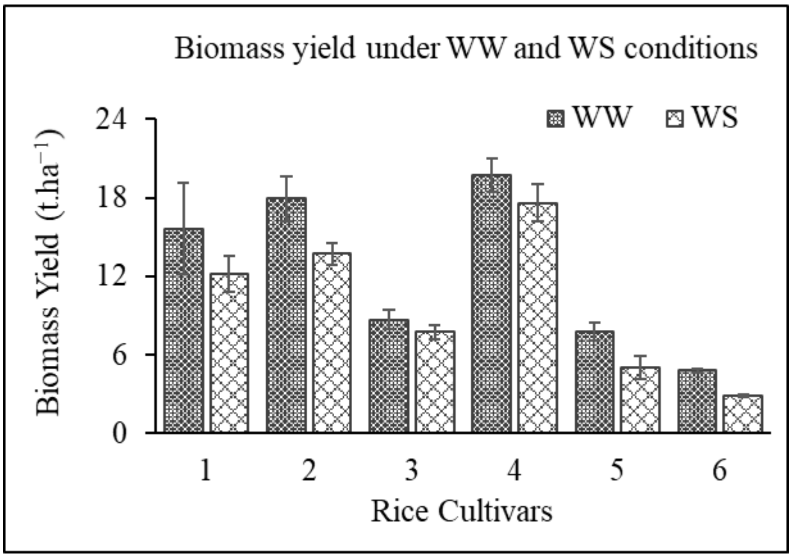

Figure 8: Effect of well−watered and water stressed treatments on biomass yield of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.2. Cultivar stability assessment

Stress susceptibility index (SSI) values ranged 0.51–1.97 under water stress, whereas relative yield (RY) for biomass under WW, (RYWW) and WS (RYWS) vary between from 0.24 to 1.00 and 0.16 to 1.00, respectively (Table 2). SSI for BY indicated that cultivars 3 and 4 exhibited comparatively smaller reductions in their biomass yield and were found to be stress−tolerant and high−yielding for biomass production. Cultivars 3 and 4 exhibited comparatively smaller reductions in their biomass yield maintaining plant performance under water stress which exhibited their stress tolerance capability. Bruckner and Frohberg (1987), stated that cultivars having low SSI index values, (less than 1) could be believed as stress tolerant cultivars as they showed comparatively smaller reductions in yield under water stress conditions when compared with well−watered conditions. Relative yield was taken into consideration as it gives the measure of relatively lower or higher yield under water stress conditions. Cultivars 3 and 4 were found stress tolerant as well as relatively high yielding for biomass production. Tuong and Bouman, (2000) also stated that tolerant cultivars maintained their yields as they maintained higher plant physiological processes and recovery of plant functions following water stress. Hence it was noticed that cultivation of stress tolerant as well as high yielding cultivars will sustain the biomass feedstock availability rather than stress susceptible cultivars.

Table 2. Stress susceptibility index (SSI) and relative yield (RY) for biomass yield in six rice cultivars.

Cultivars	Well−Watered		Water−Stressed		
	BY ± SE	**RYWW**	**BY ± SE**	**SSI**	**RYWS**
1	15.66 ± 1.99	0.79	12.18 ± 0.81	1.07	0.69
2	17.96 ± 0.99	0.91	13.70 ± 0.48	1.14	0.78
3	8.70 ± 0.44	0.44	7.75 ± 0.31	0.53	0.44
4	19.72 ± 0.74	1.00	17.61 ± 0.81	0.51	1.00
5	7.76 ± 0.41	0.39	5.05 ± 0.52	1.68	0.29
6	4.81 ± 0.08	0.24	2.84 ± 0.05	1.97	0.16
Mean	12.43	0.63	9.86	−	0.56

BY = mean biomass yield; ± SE = standard error, SSI = stress susceptibility index; RYW = relative yield under well−watered conditions; RYWS = relative yield under water−stressed conditions.

4.3. Biomass composition analysis and energy contents

Statistical comparisons for proximate contents (Table 3) indicated a highly significant difference among moisture contents (MC), volatile matter (VM), fixed carbon (FC), and ash contents for cultivars, treatments as well as their interactions except for a non−significant difference for VM under treatment and for FC under cultivar as well as the interaction of cultivar and treatments. Proximate composition of biomass of all cultivars was significantly altered.

Table 3. Mean squares of analysis of variance of proximate components including moisture contents, volatile matter, fixed carbon and ash contents for six rice cultivars.

SOV	df	MC	VM	FC	Ash
R	2	0.011	0.037	0.062	0.001
C	5	0.965 ***	5.524 ***	0.119 ns	5.200 ***
T	1	0.528 ***	0.139 ns	0.686 *	0.232 ***
C × T	5	0.206 ***	1.455 ***	0.157 ns	3.444 ***
Error	22	0.001	0.139	0.121	0.006
CV %		0.57	0.54	2.23	0.98

SOV = source of variation, df = degree of freedom, R = replications, C = cultivars, T = treatments, MC = moisture contents, VM = volatile matter, FC = fixed carbon, *** = highly significant ($p < 0.001$), ** = moderately significant ($p < 0.01$), * = significant ($p < 0.05$), ns = non−significant.

4.3.1. Effect of water stress on moisture contents (MC)

Values for moisture contents ranged between 6.02−7.21 for well−watered treatment, while 6.11−7.20 for water stressed treatment (Figure 9). MC were higher for cultivars 1, 2, 3, 4 and 5 by 5, 2, 14, 4 and 3%, whereas they were decreased for cultivar 6 by 4%, respectively, when compared with water stressed treatment in proximate analysis. According to Obernberger and Thek (2004), MC may vary significantly, and it is undesired component of any type of fuels. Moisture contents also influence the heating values, combustion temperatures as well as combustion efficiencies. Higher MC in biomass release lower net heating values therefore, low MC are desired in biomass for energy applications. Results indicated that MC were increased when biomass samples were used from water stressed treatment resulting a negative impact on biomass quality.

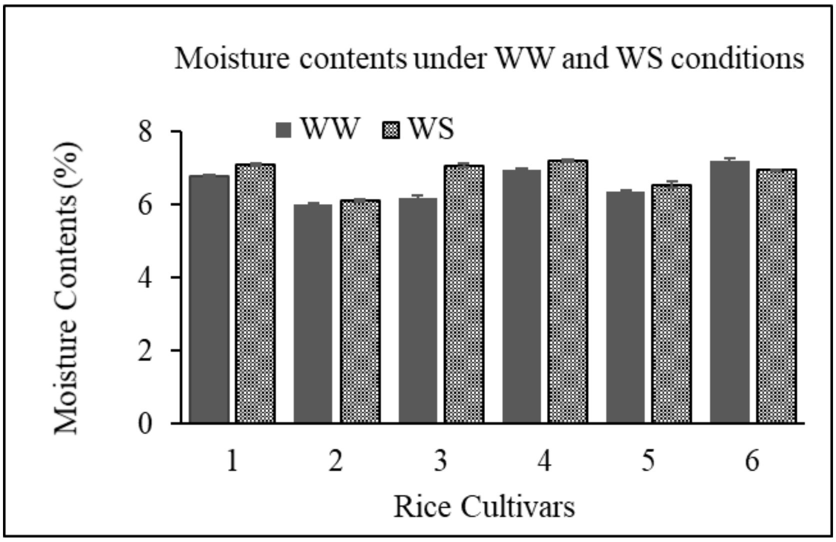

Figure 9: Effect of well−watered and water stressed treatments on moisture contents in proximate composition of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.3.2. Effect of water stress on volatile matter (VM)

Volatile matter (VM) values ranged between 68.53−70.94 for well−watered treatment, while 67.09−70.72 for water stressed treatment (Figure 10). Volatile matter was increased for cultivars 1 and 3 by 2% whereas decreased for cultivars 4 and 6 by 2%, however no change was observed for cultivars 2 and 5. Volatile matter is desired component in biomass and according to Demirbas, (2004) and Vassilev *et al.* (2010) it usually comprises of CO, CO_2, H_2, MC, and tars. Depending upon raw materials, generally biomass contains higher VM ranging from 75% to 90% (Khan et al., 2009). Volatile matter was found in significant positive correlation with higher heating value, biomass yield and energy potential while in significant correlation with ash. Higher ash contents resulted in lower volatile matter.

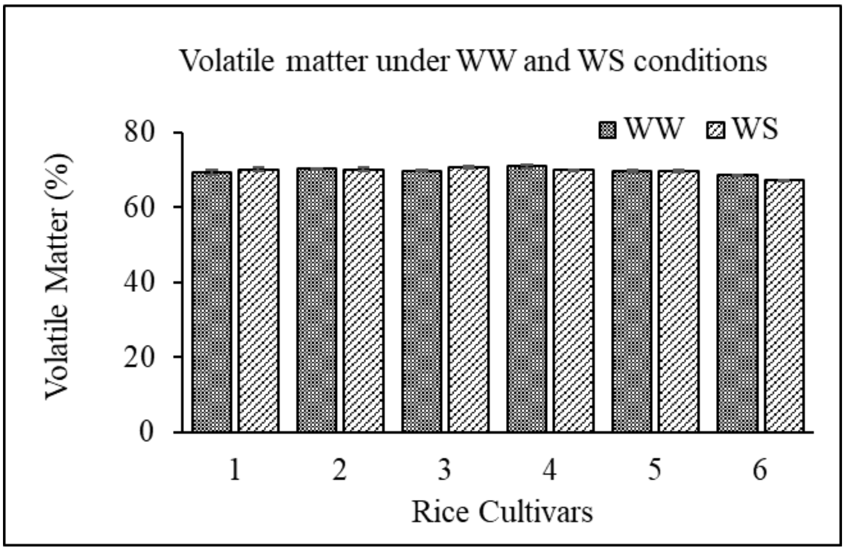

Figure 10: Effect of well−watered and water stressed treatments on volatile matter in proximate composition of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.3.3. Effect of water stress on fixed carbon (FC)

Composition analysis indicated that fixed carbon (FC) contents were between 15 and 16% and values ranged between 15.52–16.00 for well−watered treatment and 15.14–15.69 for water stressed treatment, respectively (Figure 11). FC contents were increased for cultivar 1 by 1% whereas they were decreased for cultivars 3, 4 and 6 by 3, 4 and 5%, respectively, and no change was observed for cultivars 2 and 5. According to a report by UN, (UNEP, 2006) FC represents to free carbon which is not bound with other components. Kreil and Broekema, (2010) stated that in a combustion system FC produces char and burnt as solid substance. Higher FC results in positive on combustion process. Vassilev et al. (2010) stated that herbaceous agricultural biomass usually contains higher FC contents and according to Yang et al. (2005), FC contents should be expected 7−20%. In this study, composition analysis indicated that FC contents were between 15 and 16 %. fixed carbon contents were negatively correlated with ash whereas it was in positive correlation with biomass yield and energy potential.

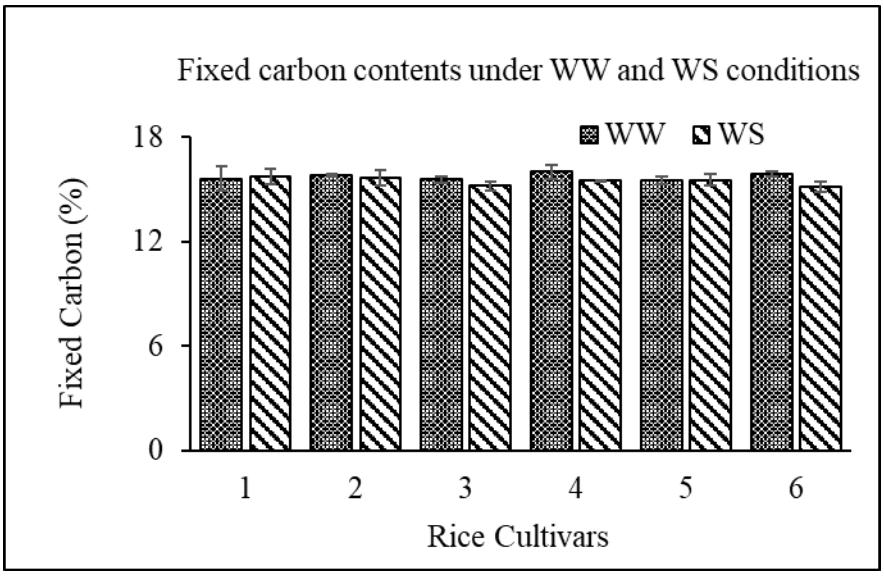

Figure 11: Effect of well−watered and water stressed treatments on fixed carbon contents in proximate composition of lowland rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.3.4. Effect of water stress on ash contents

Values for ash contents ranged between 6.11−8.53 for well−watered treatment, while 7.02−10.82 for water stressed treatment (Figure 12). Ash contents were increased for cultivars 2, 4 and 6 by 4, 22 and 29%, whereas they were decreased for cultivars 1, 3 and 5 by 15, 17 and 4%, respectively. Ash is considered as incombustible matter in biomass, which is not only undesirable material, but also higher ash contents result in high carbon and gas emissions. Ash was negatively correlated with higher heating value, biomass yield and energy potential. Another important factor is “Slag” formation in boilers or furnaces during combustion process which results because of lower melting point of ash in thermal processing. Hodgson et al. (2010), stated that slag formation in boilers or furnaces hinders the energy conversion and combustion efficiency is decreased. Results indicated that although cultivars 2 and 4 were stress tolerant and maintained their biomass yield but their biomass quality was affected and as ash contents were increased which are undesired. Results exhibited that cultivation of such cultivars over time or due to farmer's preference and occurrence of water stress will not only impact biomass quantity but will also impact the biomass quality. Increase in ash contents of specific cultivars under water stress indicted that biomass obtained from these cultivars will produce more ash limiting the combustion efficiency.

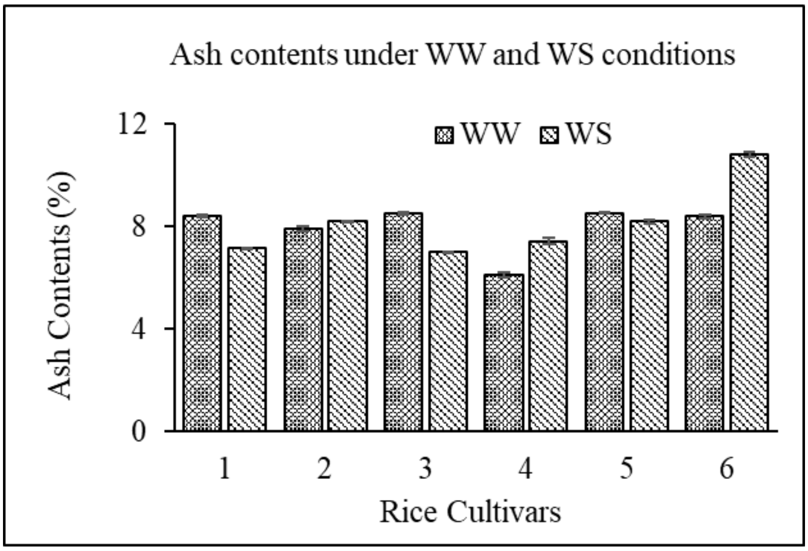

Figure 12: Effect of well−watered and water stressed treatments on ash contents in proximate composition of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.4. Effect of water stress on lignocellulosic composition

There was a highly significant difference for cellulose, hemicellulose, lignin and extractives for cultivars, treatments and their interactions and a non−significant difference for hemicellulose under treatments (Table 4). Water stress caused the variation in lignocellulosic response for all cultivars under water stress treatment. Cultivar 3 exhibited larger variations whereas cultivar 4 exhibited slight variations in lignocellulosic composition under water stress as compared to other cultivars.

Table 4. Mean squares of analysis of variance of lignocellulosic analysis of six rice cultivars.

SOV	df	Cellulose	Hemicellulose	Lignin	Extractives
Replication	2	0.012	0.016	0.006	0.003
Cultivars (C)	5	5.606 ***	6.562 ***	0.039 ***	16.708 ***
Treatment (T)	1	7.471 ***	0.043 ns	0.777 ***	14.618 ***
C × T	5	6.304 ***	6.733 ***	0.300 ***	22.527 ***
Error	22	0.050	0.052	0.002	0.008
CV %		0.730	0.860	1.360	0.220

SOV = source of variation, df = degree of freedom, R = replications, C = cultivars, T = treatments, CV = coefficient of variation, *** = highly significant ($p < 0.001$), ns = non−significant.

4.4.1. Effect of water stress on cellulose contents

Cellulose contents ranged between 29.44−31.33% for well−watered treatment, while 29.80−34.20% for water stressed treatment (Figure 13). Cellulose contents were increased for cultivars 1, 3 and 6 by 4, 16 and 3%, whereas they were decreased for cultivars 2 and 5 by 4 and 1%, respectively, whereas no change was observed for cultivar 4 under water stress. Higher cellulose contents in biomass contributes to higher energy output and plant cultivars having higher cellulose contents in their biomass will yield higher energy potentials (Kim et al., 2013). During energy conversion process, higher levels of cellulose and low levels of lignin and extractives are desired. Palamanit et al. (2019) found that during pyrolysis, the biomass with higher levels of cellulose contents promoted relatively higher yields of bio−oil and liquid than the biomass having higher levels of lignin contents. It was due to the reason that thermal disintegration and conversion of cellulose is much easier than the lignin.

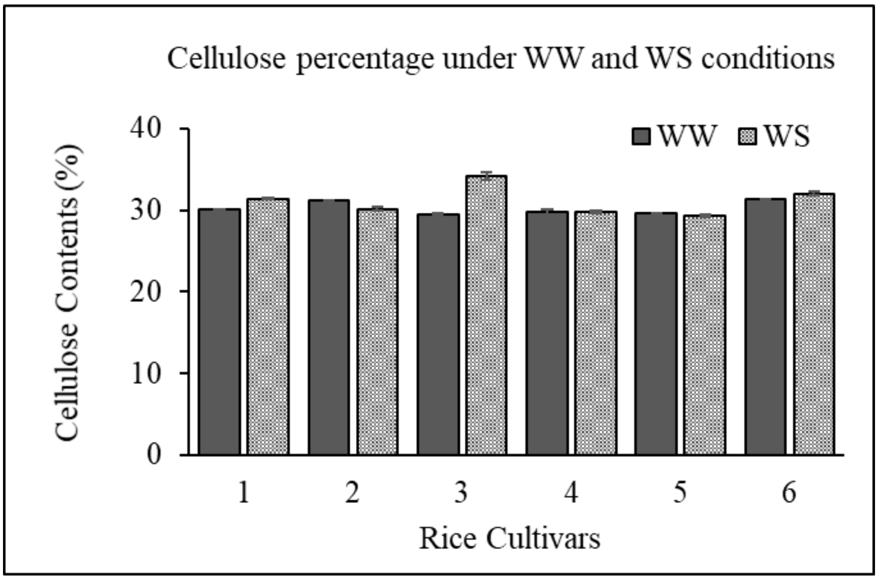

Figure 13: Effect of well−watered and water stressed treatments on cellulose contents of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.4.2. Effect of water stress on hemicellulose contents

Hemicellulose contents ranged between 25.08−28.30% for well−watered treatment, while 24.82−29.40% for water stressed treatment (Figure 14). Hemicellulose contents were increased for cultivars 1, 2, and 3 by 3, 6 and 10% whereas they were decreased for cultivars 4, 5 and 6 by 1, 3 and 12%, respectively, under water stress. Higher hemicellulose contents in biomass contributes to higher energy output and plant cultivars having higher hemicellulose contents in their biomass will yield higher energy potentials (Kim et al., 2013). During the energy conversion process, higher levels of hemicellulose are desired. Palamanit et al. (2019) also found that during pyrolysis, the biomass with higher levels of hemicellulose contents promoted relatively greater yields of bio−oil and liquid than the biomass having higher levels of lignin contents. It was due to the reason that thermal disintegration and conversion of hemicellulose is much easier than the lignin.

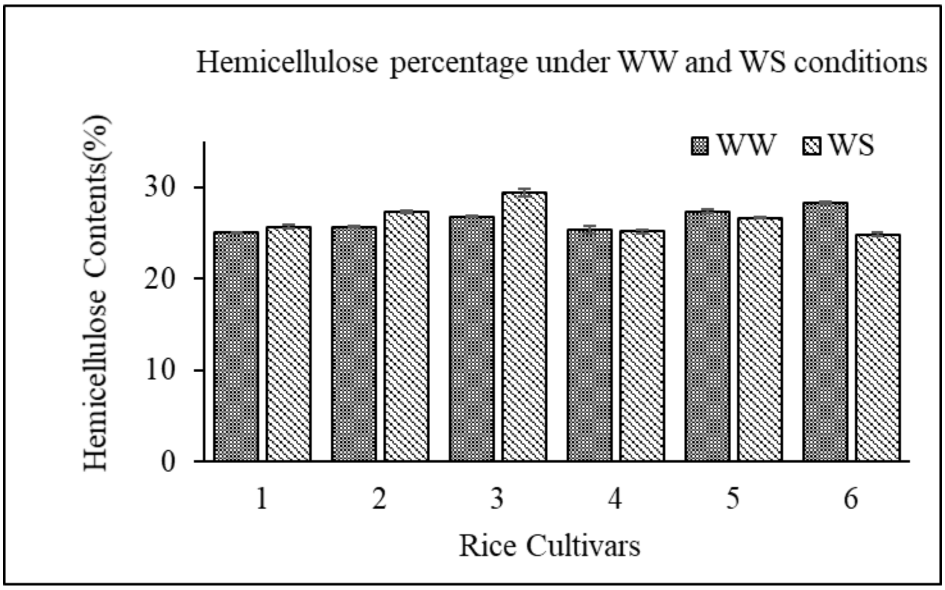

Figure 14: Effect of well−watered and water stressed treatments on hemicellulose contents of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.4.3. Effect of water stress on lignin contents

Lignin contents ranged between 2.91−3.73% for well−watered treatment, while 3.61−4.03% for water stressed treatment (Figure 15). Lignin contents were increased for cultivars 1, 3, 4 and 6 by 9, 39, 9 and 7%, whereas they were decreased for cultivars 2 and 5 by 2 and 3%, respectively, under water stress. Lower lignin contents in biomass contributes to decreased energy output and plant cultivars having higher lignin contents in their biomass will yield lower energy potentials as compared to plant cultivars having lower lignin contents (Kim et al., 2013). During the energy conversion process, lower levels of lignin are desired. Palamanit et al. (2019) also found that during pyrolysis, the biomass with higher levels of cellulose and hemicellulose contents promoted relatively greater yields of bio−oil and liquid than the biomass having higher levels of lignin contents. It was due to the reason that thermal disintegration of lignin is harder than that of cellulose and hemicellulose.

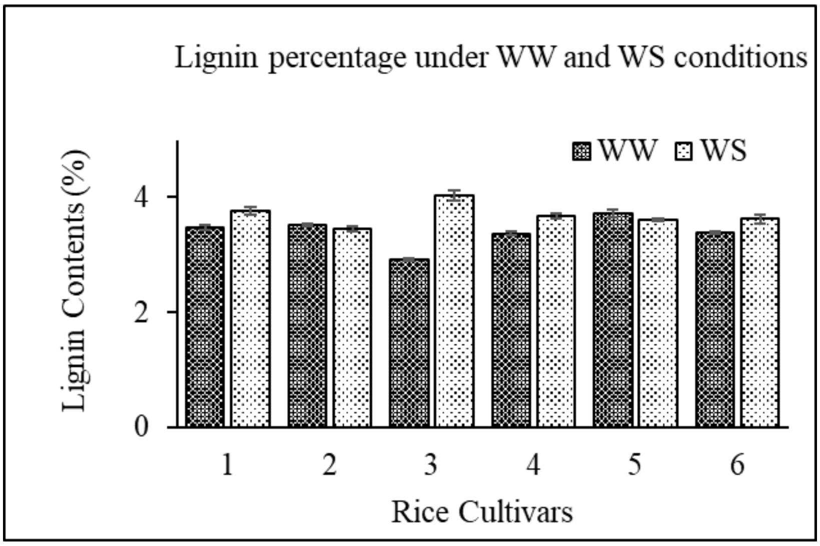

Figure 15: Effect of well−watered and water stressed treatments on lignin contents of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.4.4. Effect of water stress on extractives

Percentage for extractives ranged between 36.98−41.49% for well−watered treatment, while 32.37−41.33% for water stressed treatment (Figure 16). Extractives were increased for cultivars 5 and 6 by 3 and 7%, whereas they were decreased for cultivars 1, 2 and 3 by 5, 1 and 21%, respectively, whereas no change was observed for cultivar 4 under water stress. During the energy conversion process, low levels of extractives are desired and plant biomass having higher levels of lignin and extractives produce relatively lower yields.

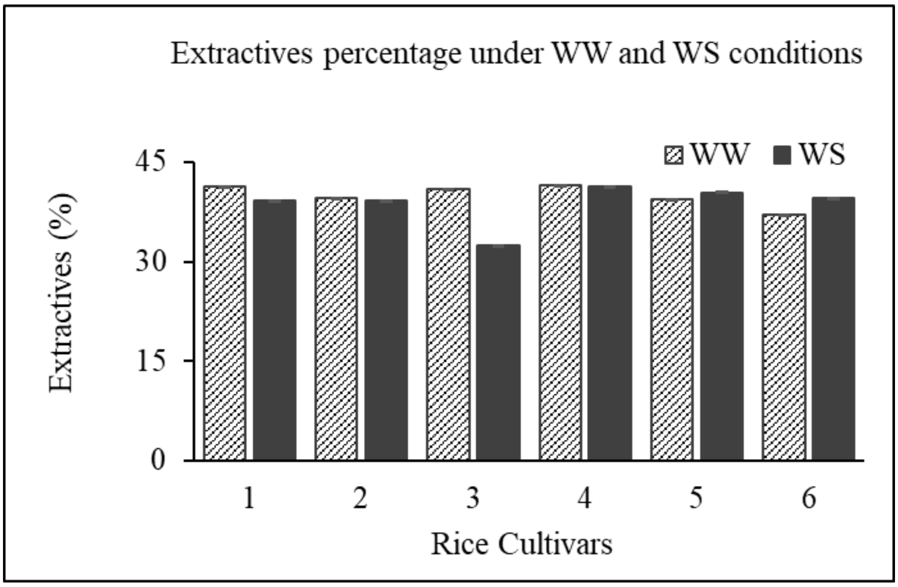

Figure 16: Effect of well−watered and water stressed treatments on extractives of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

It was observed that water stress increased the levels of lignin and extractives for cultivars 1, 3, 4 and 6 whereas decreased for cultivars 2 and 5. Although cellulose for cultivar 6 and cellulose and hemicellulose were increased for cultivars 1 and 3, but still, it is point of concern that increase in lignin concentration will require higher energy input during energy conversion process. Cultivar 4 maintained the concentration of cellulose and hemicellulose under water stress despite the increase in lignin and extractives. Cultivars having higher cellulose and hemicellulose concentration in their biomass will be able to exhibit higher energy potential as compared to others. Kim et al. (2013) also stated that biomass containing higher cellulose and hemicellulose contents produced higher bio−oil yield. Results indicated that increase in lignin contents of biomass produced under water stress, will impact the quality of energy output. There might be a fact that reduction in hemicellulose of cultivar 6 may not affect energy output as cellulose concentration was increased. This is because Qu et al. (2011) also found that cellulose provided a high bio−oil yield during pyrolysis because cellulose is comparatively more volatile as compared to hemicellulose. However, cellulose and hemicellulose alone cannot predict and constitute the energy output and potential from specific area grown as concentration of these components will be computed with the produced biomass and biomass results indicted a negative correlation of cultivar 6 response to water stress and relative yield.

4.5. Higher heating value (HHV) and energy potential (E)

Statistical comparisons indicated a highly significant difference among higher heating value (HHV), energy potential (E), cultivars and treatments as well as their interactions except for a non−significant difference for energy potential under the interaction of cultivar and treatments (Table 5). Water stress significantly altered that HHV and energy potential of rice biomass.

Table 5. Mean squares of analysis of variance of higher heating value (HHV) and potential bioenergy (E) for six rice cultivars.

SOV	df	HHV	E
Replications	2	0.001	331007
Cultivars	5	0.149 ***	84120000 ***
Treatments	1	0.008 **	24310000 ***
Cultivars × Treatments	5	0.046 ***	834913 ns
Error	22	0.002	818514
CV %		0.41	12.82

SOV = source of variation, df = degree of freedom, HHV = higher heating value, E = Potential bioenergy, *** = highly significant ($p < 0.001$), ** = moderately significant ($p < 0.01$), * = significant ($p < 0.05$), ns = non−significant.

4.5.1. Effect of water stress on higher heating value (HHV)

Higher heating value values ranged between 11.18−11.58 for well−watered treatment, while 10.91−11.51 for water stressed treatment (Figure 17). Higher heating value was increased for cultivars 1 and 3 by 2%, whereas it was decreased for cultivars 4 and 6 by 2 and 3%, respectively, whereas no significant change was observed for cultivars 2 and 5. Heating values are considered as energy contents of fuel as standard which is usually described as lower heating value or HHV. HHV was positively correlated with volatile matter while negatively correlated with ash. Voca et al. (2016) found that there was no significant difference observed for the HHV of Plum and it is possible that different cultivars may exhibit similar HHV. HHV values were found to be comparable with the results 15.09 and 15.61 by the findings of Kamruzzaman and Islam, (2011), Grover et al. (2002) and Jenkins M. et al. (1998). Heating values depend upon the concentration of FC, VM and ash. According to Shrivastava et al. (2021) biomass containing higher FC, VM and low ash contents will deliver higher heating values. Cultivar 2, 4 and 6 exhibited that ash contents were increased while remaining proximate properties were decreased under water stress. It indicated that water stress influenced the biomass development and proximate composition which ultimately influenced heating values. Results supported the hypothesis that biomass obtained from cultivation of such type of cultivars over time and water shortage in future may influence heating potential of rice biomass.

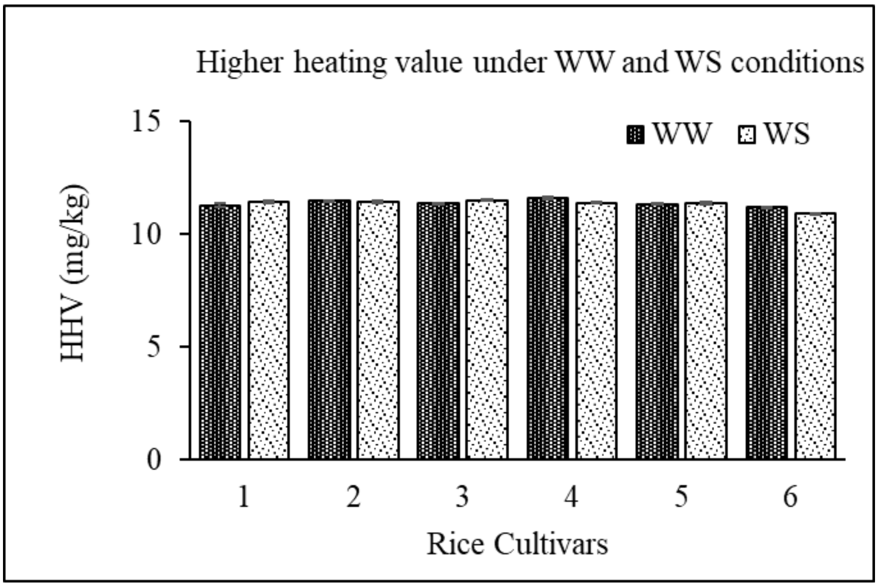

Figure 17: Effect of well–watered and water stressed treatments on higher heating value of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.5.2. Effect of water stress on energy potential (E)

All cultivars exhibited a higher potential for bioenergy under well–watered conditions (Figure 18). Values ranged between 2990 and 12,685 kWh.ha^{-1} for well–watered treatment, and 1724 and 11,142 kWh.ha^{-1} for water stressed treatment, respectively (Figure 18). Maximum bioenergy potential was achieved by cultivar 6 due to higher biomass production. Bioenergy potential was reduced under water stress for all cultivars including cultivar 1, 2, 3, 4, 5 and 6 by 21%, 24%, 10%, 12%, 35% and 42%, respectively (Figure 18). Bioenergy potential (E), which depends upon HHV as well as biomass production and composition, was significantly different (Table 5) due to the effect of cultivar type and water treatments except by the interaction between the cultivar type and treatments for all cultivars evaluated. All cultivars exhibited higher potential of bioenergy under well–watered conditions due to higher biomass production under well–watered conditions. Maximum bioenergy potential was achieved by cultivar 4 due to higher biomass production. Ambrosio et al. (2017) also found that higher bioenergy potential was associated with higher biomass production and HHV. Bioenergy potential was found significantly positive correlated with HHV and biomass yield while significantly negative correlated with ash (Table 7). These results indicated that higher biomass producing cultivars generate higher energy potential and reduction in biomass yield will negatively impact the energy potential. Biomass productivity is dependent upon crop growing conditions, planting density, fertilizer and nutrient availability, crop management practices and climatic factors which can however limit the biomass production. Cultivation of low biomass producing cultivars over time, or by farmers choice for grain will also negatively impact biomass availability to biomass–based powerplants. In a crop management study, it was observed that, heating value, and the potential for energy for power generation from maize crop along with dry matter productivity and grain production was increased by nitrogen fertilizer application while it was slightly influenced by inter–row spacing (Ambrosio et al., 2017). In this study although some cultivars *i.e.*, cultivar 4 exhibited smaller reduction in biomass yield under water stress and rice fields grown with cultivar 4 will be able to contribute higher bioenergy but results indicated the potential decline in biomass feedstock availability, biomass quality and overall energy output if water stress or drought occurred during growing season.

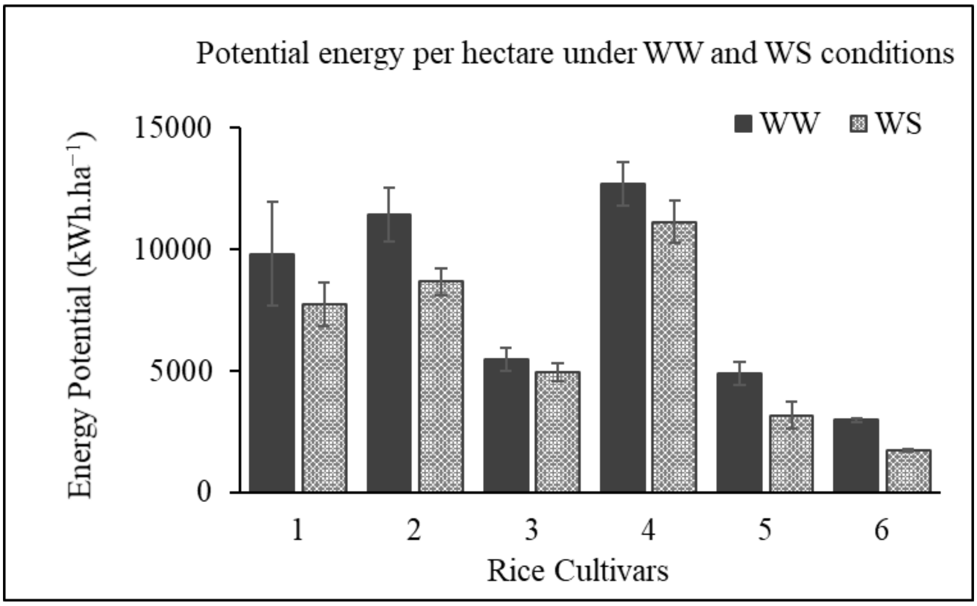

Figure 18: Effect of well−watered and water stressed treatments on energy potential of rice cultivars. Vertical bars refer to ± standard errors for average data from three replicates.

4.6. Correlation Analysis

4.6.1. Correlation among biomass contributing parameters

Pearson's correlation coefficients matrix for biomass contributing parameters (Table 6) indicated that stem numbers were significant (p < 0.05) negatively correlated with days to maturity with coefficient value of −0.327 whereas stem height was significantly (p < 0.001) positive correlated with days to maturity with coefficient value of 0.690. Biomass yield was significantly positive (p < 0.001) correlated with days to maturity and stem height with coefficient values of 0.779 and 0.929 respectively. Biomass yield is also influenced by the performance of biomass contributing parameters in rice *i.e.*, stem height and stem numbers. Higher stem height contributes to increase in rice plant biomass yield. Knoll et al. (2021) also observed that mature stem height was highly significantly correlated with biomass yield.

Table 6. Combined Pearson's correlation coefficients matrix for days to maturity, stem height, stem numbers and biomass yield.

Traits	Days to maturity	Stem numbers	Stem height
Stem numbers	-0.327^{*}		
Stem height	0.690^{***}	0.030^{ns}	
Biomass yield	0.779^{***}	0.024^{ns}	0.929^{***}

*** = highly significant ($p < 0.001$), * = significant ($p < 0.05$), ns = non−significant.

4.6.2. Correlation among proximate properties

Correlation matrix for proximate properties (Table 7) indicated a significant negative correlation for ash with VM ($p < 0.001$) and FC ($p < 0.05$) with Pearson's coefficient of −0.874 and −0.326 respectively. HHV was highly significant ($p < 0.001$) and positively correlated with VM and correlated significantly ($p < 0.001$) negative with ash with coefficient values 0.996 and −0.905 respectively. BY had highly significant ($p < 0.001$) positive correlation with VM and HHV with coefficient value 0.592 and 0.615 respectively whereas significantly ($p < 0.05$) positive correlated with FC with coefficient value 0.328. A highly significant ($p < 0.001$) negative correlation of BY with ash for coefficient value −0.618 was also observed. Energy potential was found highly significant ($p < 0.001$) and positively correlated with VM, HHV and BY with values 0.603, 0.626 and 0.999, whereas a significant positive correlation (p < 0.05) correlation was observed among E and FC with coefficient value 0.325. However, a highly significant (p < 0.001) and negative correlation was observed among E and ash contents with coefficient value of −0.627. Ambrosio et al. (2017) found that higher bioenergy potential was associated with higher biomass production and HHV. Bioenergy potential was found significantly positive correlated with HHV and biomass yield while significantly negative correlated with ash. These results indicated that higher biomass producing cultivars generate higher energy potential and reduction in biomass yield will negatively impact the energy potential.

Table 7. Combined Pearson's correlation coefficients matrix for moisture contents (MC), volatile matter (VM), fixed carbon (FC), ash, higher heating value (HHV), biomass yield (BY) and energy potential (E).

Components	**MC**	**VM**	**FC**	**Ash**	**HHV**	**BY**
VM	-0.181^{ns}					
FC	-0.083^{ns}	0.025^{ns}				
Ash	-0.189^{ns}	-0.874^{***}	-0.326^{*}			
HHV	-0.170^{ns}	0.996^{***}	0.116^{ns}	-0.905^{***}		
BY	-0.117^{ns}	0.592^{***}	0.328^{*}	-0.618^{***}	0.615^{***}	
E	-0.117^{ns}	0.603^{***}	0.325^{*}	-0.627^{***}	0.626^{***}	0.999^{***}

*** = highly significant (p < 0.001), * = significant (p < 0.05), ns = non−significant.

4.6.3. Correlation among lignocellulosic properties

Correlation analysis among lignocellulosic properties (Table 8) indicated a moderately significant ($p < 0.01$) and positive correlation between cellulose and hemicellulose of value 0.385. Lignin was highly significant ($p < 0.001$) and positively correlated with cellulose with coefficient value 0.583. Extractives were highly significantly ($p < 0.001$) negative correlated with cellulose, hemicellulose, and lignin with coefficient values −0.850, −0.806 and −0.550 respectively (Table 8). Whereas no significant correlation was observed among lignin and hemicellulose. Higher cellulose and hemicellulose contents in biomass contributes to higher energy output and plant cultivars having higher cellulose and hemicellulose contents will yield higher energy potentials (Kim et al., 2013). During energy conversion process, higher levels of cellulose and low levels of lignin and extractives are desired. Palamanit et al. (2019) found that during pyrolysis, biomass with higher levels of cellulose and hemicellulose contents promoted relatively higher yields of bio−oil and liquid than the biomass having higher levels of lignin contents.

Table 8. Combined Pearson's correlation coefficients matrix for lignocellulosic components.

Components	Cellulose	Hemicellulose	Lignin
Hemicellulose	0.385^{**}		
Lignin	0.583^{***}	0.192^{ns}	
Extractives	-0.850^{***}	-0.806^{***}	-0.550^{***}

*** = highly significant ($p < 0.001$), ** = moderately significant ($p < 0.01$), ns = non−significant.

Chapter 5

Conclusion and Suggestions

5.1. Rice biomass production performance

Study revealed that water resulted in negative impact on all cultivars performance affecting the biomass composition hence quality, and biomass feedstock availability. Cultivars Hom Pathum and Dum Ja found to be stress tolerant as they exhibited smaller reductions in their biomass yield under water stress indicating that cultivation of stress tolerant cultivars will help to stabilize biomass yield and availability as compared to susceptible cultivars.

5.2. Energy contents and energy potential

Proximate composition of biomass of all cultivars was altered and quality of biomass of cultivars Hom Chan, Dum Ja and RD−15 was decreased due to increase in ash contents by 4−29%. Ash was negatively correlated with higher heating value (HHV), biomass yield and energy potential (E). Lignin and extractives which are undesired in higher concentration were increased for cultivars Hom Nang Kaew, Hom Pathum, Dum Ja, Khao Dawk Mali−105 and RD−15. Although Hom Pathum and Dum Ja maintained their biomass yield, proximate and lignocellulosic analysis indicated that the quality of the biomass of these cultivars was compromised. Energy potential, which is dependent upon HHV, and biomass production potential was decreased 10−42% under water stress. It was concluded that energy potential will be affected if low biomass yielding, stress susceptible cultivars are grown, water stress is occurred, or farmers continue to grow specific cultivars. In such case, biomass availability will be reduced to established small biomass−based power plants along with lowered biomass quality resulting a decline in final energy potential.

References:

AEEI. 2015. Thailand Alternative Energy Situation: Alternative Energy and Efficiency Information Center. Bangkok, Thailand.

Al-Hakimi, A. M. A. 2006. Counteraction of Drought Stress on Soybean Plants by Seed Soaking in Salicylic Acid. *International Journal of Botany* 2, 421–426. doi:10.3923/ijb.2006.421.426.

Ambrosio, R., Pauletti, V., Barth, G., Povh, F. P., Silva, D. A. da, and Blum, H. 2017. Energy potential of residual maize biomass at different spacings and nitrogen doses. *Ciência e Agrotecnologia* 41, 626–633. doi:10.1590/1413-70542017416009017.

Anantha, M. S., Patel, D., Quintana, M., Swain, P., Dwivedi, J. L., Torres, R. O., et al. 2016. Trait combinations that improve rice yield under drought: Sahbhagi Dhan and new drought-tolerant varieties in South Asia. *Crop Science* 56, 408–421. doi:10.2135/cropsci2015.06.0344.

Antongiovanni, M., and Sargentini, C. 1991. Variability in chemical composition of straws. *Option Méditérranéennes* 16, 49–53.

Ball, R. A., Oosterhuis, D. M., and Mauromoustakos, A. 1994. Growth Dynamics of the Cotton Plant during Water-Deficit Stress. *Agronomy Journal* 86, 788–795. doi:https://doi.org/10.2134/agronj1994.00021962008600050008x.

Barz, M., and Delivand, M. K. 2011. Agricultural Residues as Promising Biofuels for Biomass Power Generation in Thailand. *Journal of Sustainable Energy & Environment Special Issue*, 21–27.

Bruckner, P. L., and Frohberg, R. C. 1987. Stress Tolerance and Adaptation in Spring Wheat 1 . *Crop Science* 27, 31–36. doi:10.2135/cropsci1987.0011183x002700010008x.

Cheewaphongphan, P., and Garivait, S. 2013. Bottom up approach to estimate air pollution of rice residue open burning in Thailand. *Asia-Pacific Journal of Atmospheric Sciences* 49, 139–149. doi:10.1007/s13143-013-0015-0.

Cheewaphongphan, P., Junpen, A., Kamnoet, O., and Garivait, S. 2018. Study on the potential of rice straws as a supplementary fuel in very small power plants in Thailand. *Energies* 11, 1–21. doi:10.3390/en11020270.

Cuiping, L., Yanyongjie, Chuangzhi, W., and Haitao, H. 2004. Study on the distribution and quantity of biomass residues resource in China. *Biomass and Bioenergy* 27, 111–117. doi:10.1016/j.biombioe.2003.10.009.

Davatgar, N., Neishabouri, M. R., Sepaskhah, A. R., and Soltani, A. 2009. Physiological and morphological responses of rice (Oryza sativa L.) to varying water stress management strategies. *International Journal of Plant Production* 3, 19–32. doi:10.22069/ijpp.2012.660.

Debaeke, P., and Aboudrare, A. 2004. Adaptation of crop management to water-limited environments. *European Journal of Agronomy* 21, 433–446. doi:https://doi.org/10.1016/j.eja.2004.07.006.

DEDE. 2016. Alternative Energy and Efficiency Information Center, Department of Alternative Energy Development and Efficiency,. Bangkok, Thailand.

Demirbas, A. 2004. Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science* 30, 219–230. doi:10.1016/j.pecs.2003.10.004.

Duangpan, S., Tongchu, Y., Hussain, T., Eksomtramage, T., and Onthong, J. 2022. Beneficial Effects of Silicon Fertilizer on Growth and Physiological Responses in Oil Palm. *Agronomy* 12. doi:10.3390/agronomy12020413.

Ellabban, O., Abu-Rub, H., and Blaabjerg, F. 2014. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews* 39, 748–764. doi:https://doi.org/10.1016/j.rser.2014.07.113.

Emerson, R., Hoover, A., Ray, A., Lacey, J., Cortez, M., Payne, C., et al. 2014. Drought effects on composition and yield for corn stover, mixed grasses, and Miscanthus as bioenergy feedstocks. *Biofuels* 5, 275–291. doi:10.1080/17597269.2014.913904.

Fischer, R. A., and Maurer, R. 1978. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research* 29, 897–912. doi:10.1071/AR9780897.

Frankl, P., Brown, A., and Dobrotkova, Z. 2013. Global tracking framework: sustainable energy for all. *Renewable Energy* 4, 193–250.

Garrote, G., Domínguez, H., and Parajó, J. C. 2002. Autohydrolysis of corncob: Study of non-isothermal operation for xylooligosaccharide production. *Journal of Food Engineering* 52, 211–218. doi:10.1016/S0260-8774(01)00108-X.

Grover, P. D., Iyer, P. V. R., and Rao, T. R. 2002. *Biomass thermo-chemical characterization*. 3rd ed. IIT – Delhi and MNES.

Hashem, M., Ali, E. H., and Abdel-Basset, R. 2013. Recycling rice straw into Biofuel "ethanol" by Saccharomyces cerevisiae and Pichia guilliermondii. *Journal of Agricultural Science and Technology* 15, 709–721.

Hodgson, E. M., Fahmi, R., Yates, N., Barraclough, T., Shield, I., Allison, G., et al. 2010. Miscanthus as a feedstock for fast-pyrolysis: Does agronomic treatment affect quality? *Bioresource Technology* 101, 6185–6191. doi:10.1016/j.biortech.2010.03.024.

Hussain, T., Anothai, J., Nualsri, C., and Soonsuwon, W. 2018. Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian Journal of Agricultural Research* 52, 140–145. doi:10.18805/IJARe.A-321.

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T., and Taweekun, J. 2021a. Potential impacts of water stress on rice biomass composition and feedstock availability for bioenergy production. *Sustainability (Switzerland)*. doi:10.3390/su131810449.

Hussain, T., Hussain, N., Ahmed, M., Nualsri, C., and Duangpan, S. 2021b. Responses of lowland rice genotypes under terminal water stress and identification of drought tolerance to stabilize rice productivity in southern thailand. *Plants* 10. doi:10.3390/plants10122565.

Hussain, T., Hussain, N., Ahmed, M., Nualsri, C., and Duangpan, S. 2022. Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. *Sustainability (Switzerland)* 14, 1–17.

doi:10.3390/su14041997.

Ichsan, C. N., Basyah, B., Zakaria, S., and Efendi, E. 2020. Differences of water status and relationship with roots growth and yield of rice under water stress. *Systematic Reviews in Pharmacy* 11, 611–618.

Imam, T., and Capareda, S. 2012. Characterization of bio-oil, syn-gas and bio-char from switchgrass pyrolysis at various temperatures. *Journal of Analytical and Applied Pyrolysis* 93, 170–177. doi:10.1016/j.jaap.2011.11.010.

Jenkins M., B., Bexter L., L., Miles R. Jr., T., and Miles R., T. 1998. Combustion Properties of Biomass Flash. *Fuel Processing Technology* 54, 17–46.

Kalt, G., and Kranzl, L. 2011. Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach. *Applied Energy* 88, 3665–3684. doi:https://doi.org/10.1016/j.apenergy.2011.03.014.

Kamruzzaman, M., and Islam, A. S. 2011. Physical and Thermochemical Properties of Rice Husk In Bangladesh. *International Journl of BioResources* 11, 45–49. doi:10.1080/00908319708908904.

Kavar, T., Maras, M., Kidrič, M., Šuštar-Vozlič, J., and Meglič, V. 2008. Identification of genes involved in the response of leaves of Phaseolus vulgaris to drought stress. *Molecular Breeding* 21, 159–172. doi:10.1007/s11032-007-9116-8.

Khalil, A. K., Mubarak, A. M., and Kaseb, S. A. 2010. Road map for renewable energy research and development in Egypt. *Journal of Advanced Research* 1, 29–38. doi:10.1016/j.jare.2010.02.003.

Khan, A. A., de Jong, W., Jansens, P. J., and Spliethoff, H. 2009. Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Processing Technology* 90, 21–50. doi:10.1016/j.fuproc.2008.07.012.

Kim, S. S., Ly, H. V., Kim, J., Choi, J. H., and Woo, H. C. 2013. Thermogravimetric characteristics and pyrolysis kinetics of Alga Sagarssum sp. biomass. *Bioresource Technology* 139, 242–248. doi:10.1016/j.biortech.2013.03.192.

Knoll, J. E., Anderson, W. F., Missaoui, A., Hale, A., and Hanna, W. W. 2021. Biomass production and stability of five energycane cultivars at two latitudes in Georgia. *Agrosystems, Geosciences & Environment* 4, 1–14. doi:10.1002/agg2.20146.

Kondo, M., Murty, M. V. R., Aragones, D. V., Okada, K., Winn, T., and Kwak, K. S. 1999. “Characteristics of the root system and water uptake in upland rice,” in *Genetic improvement of rice for water limited environments*, eds. O. Ito, J. O’Toole, and B. Hardy (Los Banos, Philippines: International Rice Research Institute), 117–131.

Kreil, K., and Broekema, S. 2010. Chemical and Heat Value Characterization of Perennial Herbaceous Biomass Mixtures; Analysis Report; Microbeam Technologies. Grand Forks, ND, USA.

Ladanai, S., and Vinterbäck, J. 2009. Global potential of sustainable biomass for energy. SLU Report 013. Available at: ISSN, 1654-9406.

Lamm, F. R., Rogers, D. ., and Manges, H. 1994. Irrigation Scheduling with Planned Soil Water Depletion. *Transactions of the ASAE* 37, 1491–1497.

doi:https://doi.org/10.13031/2013.28232.

Lawlor, D. W., and Tezara, W. 2009. Causes of decreased photosynthetic rate and metabolic capacity in water-deficient leaf cells: a critical evaluation of mechanisms and integration of processes. *Annals of botany* 103, 561–579. doi:10.1093/aob/mcn244.

Lilley, J. M., and Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars III. Phenological development, crop growth and grain yield. *Field Crops Research* 37, 225–234. doi:https://doi.org/10.1016/0378-4290(94)90101-5.

Lim, J. S., Abdul Manan, Z., Wan Alwi, S. R., and Hashim, H. 2012. A review on utilisation of biomass from rice industry as a source of renewable energy. *Renewable and Sustainable Energy Reviews* 16, 3084–3094. doi:https://doi.org/10.1016/j.rser.2012.02.051.

Lozano-García, B., and Parras-Alcántara, L. 2013. Short-term effects of olive mill by-products on soil organic carbon, total N, C: N ratio and stratification ratios in a Mediterranean olive grove. *Agriculture, Ecosystems and Environment* 165, 68–73. doi:10.1016/j.agee.2012.12.007.

Manickavelu, A., Nadarajan, N., Ganesh, S. K., Gnanamalar, R. P., and Chandra Babu, R. 2006. Drought tolerance in rice: Morphological and molecular genetic consideration. *Plant Growth Regulation* 50, 121–138. doi:10.1007/s10725-006-9109-3.

Monkham, T., Jongdee, B., Pantuwan, G., Mitchell, J. H., Sanitchon, J., and Fukai, S. 2016. Responses of rainfed lowland rice genotypes to terminal drought in Northeast Thailand. 44, 517–526.

Obernberger, I., and Thek, G. 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. *Biomass and Bioenergy* 27, 653–669. doi:10.1016/j.biombioe.2003.07.006.

OAE. Office of Agricultural Economics. 2015. Agricultural Statistics of Thailand. Office of Agricultural Rice Department. Bangkok, Thailand.

OAE. Office of Agricultural Economics. 2016. Agricultural Statistics of Thailand. Office of Agricultural Rice Department. Bangkok, Thailand.

Palamanit, A., Khongphakdi, P., Tirawanichakul, Y., and Phusunti, N. 2019. Investigation of yields and qualities of pyrolysis products obtained from oil palm biomass using an agitated bed pyrolysis reactor. *Biofuel Research Journal* 6, 1065–1079. doi:10.18331/BRJ2019.6.4.3.

Patel, D. P., Das, A., Munda, G. C., Ghosh, P. K., Bordoloi, J. S., and Kumar, M. 2010. Evaluation of yield and physiological attributes of high-yielding rice varieties under aerobic and flood-irrigated management practices in mid-hills ecosystem. *Agricultural Water Management* 97, 1269–1276. doi:10.1016/j.agwat.2010.02.018.

Qu, X., Liang, P., Wang, Z., Zhang, R., Sun, D., Gong, X., et al. 2011. Pilot Development of Polygeneration Process of Circulating Fluidized Bed Combustion combined with Coal Pyrolysis. *Chemical Engineering and Technology* 34, 61–68. doi:10.1002/ceat.201000202.

REN21. 2016. Renewable energy Policy Network for the 21st century. Renewables 2014. Global Status Report.

Rice Department. 2017. Rice Knowledge Bank: Rice Cultivate Species. Bangkok, Thailand Available at: http://www.ricethailand.go.th/Rkb/varieties/index.php-file=content.php&id=1.htm (accessed on 8 January 2017).

Saha, B. C. 2003. Hemicellulose bioconversion. *Journal of Industrial Microbiology and Biotechnology* 30, 279–291. doi:10.1007/s10295-003-0049-x.

Said, N., El-Shatoury, S. A., Díaz, L. F., and Zamorano, M. 2013. Quantitative appraisal of biomass resources and their energy potential in Egypt. *Renewable and Sustainable Energy Reviews* 24, 84–91. doi:https://doi.org/10.1016/j.rser.2013.03.014.

Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S., and Mekhilef, S. 2011. A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews* 15, 2262–2289. doi.org/10.1016/j.rser.2011.02.015.

Saikumar, S., Varma, C. M. K., Saiharini, A., Kalmeshwer, G. P., Nagendra, K., Lavanya, K., et al. 2016. Grain yield responses to varied level of moisture stress at reproductive stage in an interspecific population derived from Swarna/O. glaberrima introgression line. *NJAS - Wageningen Journal of Life Sciences* 78, 111–122. doi:10.1016/j.njas.2016.05.005.

Saxena, R. C., Adhikari, D. K., and Goyal, H. B. 2009. Biomass-based energy fuel through biochemical routes: A review. *Renewable and Sustainable Energy Reviews* 13, 167–178. doi:10.1016/j.rser.2007.07.011.

Shrivastava, P., Kumar, A., Tekasakul, P., Lam, S. S., and Palamanit, A. 2021. Comparative investigation of yield and quality of bio-oil and biochar from pyrolysis of woody and non-woody biomasses. *Energies* 14, 1–

23. doi:10.3390/en14041092.

Stone, K. C., Hunt, P. G., Cantrell, K. B., and Ro, K. S. 2010. The potential impacts of biomass feedstock production on water resource availability. *Bioresource Technology* 101, 2014–2025. doi:10.1016/j.biortech.2009.10.037.

Subbarao, G. V, Johansen, C., Slinkard, A. E., Nageswara Rao, R. C., Saxena, N. P., Chauhan, Y. S., et al. 1995. Strategies for Improving Drought Resistance in Grain Legumes. *Critical Reviews in Plant Sciences* 14, 469–523. doi:10.1080/07352689509701933.

Summers, M. D., Jenkins, B. M., Hyde, P. R., Williams, J. F., Mutters, R. G., Scardacci, S. C., et al. 2003. Biomass production and allocation in rice with implications for straw harvesting and utilization. *Biomass and Bioenergy* 24, 163–173. doi:10.1016/S0961-9534(02)00132-0.

Suzane, T., Regina, D., Savioli, M., Maria, S., and Garcia, R. 2021. Biomass and Bioenergy Sugarcane straw as a potential second generation feedstock for biorefinery and white biotechnology applications. 144. doi:10.1016/j.biombioe.2020.105896.

Swain, P., Raman, A., Singh, S. P., and Kumar, A. 2017. Breeding drought tolerant rice for shallow rainfed ecosystem of eastern India. *Field Crops Research* 209, 168–178. doi:10.1016/j.fcr.2017.05.007.

Torres, R. O., and Henry, A. 2018. Yield stability of selected rice breeding lines and donors across conditions of mild to moderately severe drought stress. *Field Crops Research* 220, 37–45. doi:10.1016/j.fcr.2016.09.011.

Tuong, T. P., and Bouman, B. A. M. 2000. Field water mangement to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management* 1615, 1–20.

Tuong, T. P., and Bouman, B. A. M. 2003. "Rice production in water-scarce environments," in *Water Productivity in Agriculture: Limits and Opportunities for Improvement* (Wallingford, UK: CAB International), 53–67.

Turner, N. C., Wright, G. C., and Siddique, K. H. M. B. T.-A. in A. 2001. "Adaptation of grain legumes (pulses) to water-limited environments," in (Academic Press), 193–231. doi:https://doi.org/10.1016/S0065-2113(01)71015-2.

UNEP. 2006. Energy Efficiency Guide for Industry in Asia. Final Report.

USDA. 2015. Thailand: Irrigation Shortage Reduces 2015/16 Rice Production. Accessed on June 25, 2020 Available at: https://apps.fas.usda.gov/psdonline/app/index.html#/app/home.

Utistham, T., Soontornrangsan, W., and Piyakuldumrong, P. 2007. Energy potential from residual biomasses in Thailand. in *3rd Energy Technology Network of Thailand (ENETT)* (Bangkok, Thailand), 1–6.

Van de Velden, M., Baeyens, J., Brems, A., Janssens, B., and Dewil, R. 2010. Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction. *Renewable Energy* 35, 232–242. doi:10.1016/j.renene.2009.04.019.

Varvel, G. E., and Wilhelm, W. W. 2008. Cob Biomass Production in the Western Corn Belt. *BioEnergy Research* 1, 223–228. doi:10.1007/s12155-008-9026-6.

Vassilev, S. V., Baxter, D., Andersen, L. K., and Vassileva, C. G. 2010. An overview of the chemical composition of biomass. *Fuel* 89, 913–933. doi:10.1016/j.fuel.2009.10.022.

Venuprasad, R., Lafitte, H. R., and Atlin, G. N. 2007. Response to direct selection for grain yield under drought stress in rice. *Crop Science* 47, 285–293. doi:10.2135/cropsci2006.03.0181.

Voća, N., Bilandžija, N., Jurišić, V., Matin, A., Krička, T., and Sedak, I. 2016. Proximate, ultimate, and energy values analysis of plum biomass by-products case study: Croatia's potential. *Journal of Agricultural Science and Technology* 18, 1655–1666.

Wang, W., Porninta, K., Aggarangsi, P., Leksawasdi, N., Li, L., Chen, X., et al. 2021. Bioenergy development in Thailand based on the potential estimation from crop residues and livestock manures. *Biomass and Bioenergy* 144, 105914. doi:10.1016/j.biombioe.2020.105914.

Wongjewboot, I., Kangsadan, T., Kongruang, S., Burapatana, V., and Pripanapong, P. 2010. Ethanol production from rice straw using ultrasonic pretreatment. in *International Conference on Chemistry and Chemical Engineering* (IEEE), 16–19.

Yang, Y. Bin, Ryu, C., Khor, A., Yates, N. E., Sharifi, V. N., and Swithenbank, J. 2005. Effect of fuel properties on biomass combustion. Part II. Modelling approach—identification of the controlling factors. *Fuel* 84, 2116–2130. doi:https://doi.org/10.1016/j.fuel.2005.04.023.

Yang, H., Yan, R., Chen, H., Lee, D. H., and Zheng, C. 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel* 86, 1781–1788.

doi:10.1016/j.fuel.2006.12.013.

Zain, N. A. M., Ismail, M. R., Puteh, A., Mahmood, M., and Islam, M. R. 2014. Impact of cyclic water stress on growth, physiological responses and yield of rice (*Oryza sativa* L.) grown in tropical environment. *Ciência Rural* 44, 2136–2141. doi:10.1590/0103-8478cr20131154.

Zulkarnain, W. M., Ismail, M. R., Ashrafuzzaman, M., Saud, H. M., and Haroun, I. C. 2009. Rice growth and yield under rain shelter house as influenced by different water regimes. *International Journal of Agriculture and Biology* 11, 566–570.

APPENDIX A

Published Paper (as a first author)

Sustainability – (Impact Factor 3.251; Indexing: Web of Science)

3/21/22, 7:27 AM Psu.ac.th Mail - Request for reprint permission letter of published articles to add in Thesis.

PRINCE OF SONGKLA UNIVERSITY

NURDA HUSSAIN <6310120017@psu.ac.th>

Request for reprint permission letter of published articles to add in Thesis.

sustainability <sustainability@mdpi.com> Tue, Mar 15, 2022 at 3:22 PM
To: NURDA HUSSAIN <6310120017@psu.ac.th>
Cc: TAJAMUL HUSSAIN <6110630006@psu.ac.th>

Dear Nurda,

Thank you very much for your e-mail. Sustainability is an open access journal, the copyright is belong to the author. There is no need to get permission from Sustainability.

If you have any problem please contact us.

Kind regards,
Elaine Li
Managing Editor

Sustainability receives its 8th Impact Factor, 3.251 (2020)

To edit a Special Issue in Sustainability, please send your proposal via
https://www.mdpi.com/journalproposal/sendproposalspecialissue/sustainability

Sustainability joins Twitter now, follow us at @Sus_MDPI and be part of our scientific community
--
Disclaimer: MDPI recognizes the importance of data privacy and protection. We treat personal data in line with the General Data Protection Regulation (GDPR) and with what the community expects of us. The information contained in this message is confidential and intended solely for the use of the individual or entity to whom they are addressed. If you have received this message in error, please notify me and delete this message from your system. You may not copy this message in its entirety or in part, or disclose its contents to anyone.

On 2022/3/14 7:11, NURDA HUSSAIN wrote:

> Dear Editor,
>
> Hope you are doing well. We need to request for reprint permission letters for our published articles in Sustainability.
> We have to add
> articles in our Thesis book therefore, kindly provide reprint
> permission for following articles.
>
> Article 1: https://doi.org/10.3390/su131810449 <https://doi.org/10.3390/su131810449> Article 2.
> https://doi.org/10.3390/su14041997 <https://doi.org/10.3390/su14041997>
> [Quoted text hidden]

sustainability

MDPI

Article

Potential Impacts of Water Stress on Rice Biomass Composition and Feedstock Availability for Bioenergy Production

Nurda Hussain [1], Mukhtar Ahmed [2], Saowapa Duangpan [3], Tajamul Hussain [3] and Juntakan Taweekun [4,*]

1 Energy Technology Program, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand; 6310120017@psu.ac.th
2 Department of Agronomy, Faculty of Crop and Food Sciences, PMAS Arid Agriculture University, Rawalpindi, Punjab 46300, Pakistan; ahmadmukhtar@uaar.edu.pk
3 Agricultural Innovation and Management Division, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand; saowapa.d@psu.ac.th (S.D.); 6110630006@psu.ac.th (T.H.)
4 Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand
* Correspondence: juntakan.t@psu.ac.th; Tel.: +66-896546846

Abstract: Bioenergy from rice biomass feedstock is considered one of the potential clean energy resources and several small biomass-based powerplants have been established in rice–growing areas of Thailand. Rice production is significantly affected by drought occurrence which results in declined biomass production and quality. The impact of water stress (WS) was evaluated on six rice cultivars for biomass quality, production and bioenergy potential. Rice cultivars were experimented on in the field under well–watered (WW) and WS conditions. Data for biomass contributing parameters were collected at harvest whereas rice biomass samples were analyzed for proximate and lignocellulosic contents. Results indicated that WS negatively influenced crop performance resulting in 11–41% declined biomass yield (BY). Stability assessment indicated that cultivars Hom Pathum and Dum Ja were stress–tolerant as they exhibited smaller reductions by 11% in their BY under WS. Statistics for proximate components indicated a significant negative impact influencing biomass quality as ash contents of Hom Chan, Dum Ja and RD-15 were increased by 4–29%. Lignocellulosic analysis indicated, an increase in lignin contents of Hom Nang Kaew, Hom Pathum, Dum Ja and RD–15 ranging 7–39%. Reduced biomass production resulted in a 10–42% reduction in bioenergy potential (E). Results proved that cultivation of stress-susceptible cultivars or farmer's choice and occurrence of WS during crop growth will reduce biomass production, biomass feedstock availability to biomass-based powerplants and affect powerplant's conversion efficiency resulting in declined bioenergy production.

Keywords: rice; water stress; biomass feedstock availability; bioenergy potential

check for updates

Citation: Hussain, N.; Ahmed, M.; Duangpan, S.; Hussain, T.; Taweekun, J. Potential Impacts of Water Stress on Rice Biomass Composition and Feedstock Availability for Bioenergy Production. *Sustainability* **2021**, *13*, 10449. https://doi.org/10.3390/su131810449

Academic Editor: Andrea Pezzuolo

Received: 11 August 2021
Accepted: 15 September 2021
Published: 19 September 2021

1. Introduction

Rice (*Oryza sativa* L.) is considered one of the main cereal crops in the world together with wheat and maize. Asia is a major rice-producing continent where rice is the main and cheap source of carbohydrates, protein, minerals and fiber along with the potential source of biomass feedstock for bioenergy. Moreover, agricultural production and energy resources are important for sustainable growth for the economy of any country to sustain economic growth. To reduce the impact of global warming and continued fuel and energy supplies, the use of renewable energy resources has become important [1]. Energy plants for bioenergy and biofuel production compete with food-producing species for land and water resources. According to Stone et al. [2], more land and water resources will be required to meet continuously increasing biofuel needs. In this scenario, crop residual biomass including rice straws and lignocellulosic biomass provides an alternative to this problem and can be converted to a number of products, i.e., biofuels [3]. Biomass is third and one of the largest energy resources worldwide [4] following coal and petroleum. These biomasses and residues are used in small powerplants as raw materials for energy generation [5]. Residues are carbon neutral which provides an advantage over fossil energy. For example, they can sequester CO_2 during the growing period and release it to the environment during the combustion process resulting in zero net addition of CO_2 [6]. However, most residues and rice biomass including straws and husk are burnt in farming areas due to a lack of appropriate collection from fields after grain harvest which results in energy loss and causes environmental and health concerns [7]. Presently, governments worldwide have planned and established strategic attention to practice renewable energy resources in structuring their national energy policies. In Thailand, efforts are made to restructure the national energy plan by increasing the share of renewable energy technologies. Biofuels, heat and electricity have been obtained continually through renewable energy and the agricultural residues are major source for heat production in Thailand [8]. According to Thailand's Alternative Energy Development Plan of 2015, Thailand had set a goal to increase the share of renewable energy to 30% in total energy consumption by 2036 which is almost 39,388 ktoe of energy [9]. AEDP's main objective is to promote renewable energy at the country's full capability. Approximately 16.40–58.28 million tons of rice biomass, which includes rice straw and husk, were estimated which contributed a major portion of available wastes from field crops. In a recent study, the bioenergy potential of rice biomass has been estimated at 807,845 TJ in seven regions of Thailand [10]. To achieve the goals of the national plan for renewable and bioenergy, a number of small biomass-based powerplants have been established in major rice-growing areas of Thailand. In these powerplants, rice biomass is used to generate electricity in Thailand and its contribution was as a second most important resource [11].

Water stress (WS) is an important factor that affects biomass production. WS leads to a decline in production and furthermore, a continuous reduced biomass production can potentially influence the biomass feedstock availability for bioenergy production [2]. WS occurs due to seasonal variations in rainfall in the current scenario of climate change. WS or drought occurrence is a serious threat to crop production for grain and biomass feedstock availability worldwide including Thailand. According to the Office of Agricultural Economics, Thailand [12], rainfed lowland rice is a major component of the rice production system of Thailand with a 9-million-hectare area. Terminal drought and WS occurrence are common in Thailand when the rice crop is at the reproductive stages and thus the crop fails to produce optimum yields [13]. Water is important during all crop growth stages, but reproductive stages are critical when, if WS occurs, a higher reduction in quantity as well as quality will be caused. According to Venuprasad et al. [14], the rice crop is extremely sensitive and vulnerable if WS occurs at reproductive growth stages. WS alters the plant biomass composition, causes substantial biomass yield (BY) losses and reduces the quality of products depending upon duration and intensity of stress. Biomass, in terms of energy, can yield three major final products including energy for heating purposes, fuel for transport and raw material for certain chemicals [15]. Energy characteristics comprise proximate components including moisture contents (MC), volatile matter (VM), fixed carbon (FC) and ash contents while characteristics of ultimate analysis include elemental composition for carbon, nitrogen, hydrogen, sulfur and higher heating value (HHV) [16]. Proximate and ultimate components are an important part of biomass as the concentration of these components affects biomass quality for devolatilization, power generation and energy output. Higher MC and ash contents affect biomass quality as well as decrease the energy conversion efficiency and energy output; therefore, low MC and ash along with high VM are desired. HHV is also an important component that yields maximum energy output. Straw biomasses are completely composed of cell walls and lignified carbohydrates, and structural proteins and minerals are present in these cell walls [17]. Lignocellulosic properties (cellulose, hemicellulose, and lignin) are important characteristics of biomass, and energy conversion and pyrolysis processes are affected by the behavior and concentration of these components [18]. The concentration of these components usually ranges from 32 to 47% for cellulose, 19 to 27% for hemicellulose and 5 to 24% for lignin [19,20]. Cellulose and hemicellulose are tightly packed layers due to the outer layer of lignin. Generally, cellulose and hemicellulose are major components in straws. In the biochemical conversion process, it is necessary to pretreat the rice biomass so that the lignin protective layer is decomposed and cellulose, as well as hemicellulose, is available to start chemical and enzyme activity. Lignin is usually converted slowly at 160–900 °C, while cellulose and hemicellulose are decomposed rapidly at 220–315 °C and 315–400 °C, respectively [21]. This indicates that the presence of higher lignin contents in biomass will make the process more complex which requires higher energy input for decomposition thus increasing the conversion cost. WS affects the biomass composition for energy contents, thus influencing the conversion efficiency. According to Al-Hakimi et al. [22], cellulose, lignin, and pectin's concentration was potentially decreased whereas the concentration of hemicellulose was increased in soybean's shoots when grown under WS.

Continuous and viable biomass feedstock supply is necessary for biofuel production [23]; however, WS occurrence impacts the quality and BY. According to Emerson et al. [23], it is crucial to investigate the impact of WS on crop production and quantification of impacts of WS on crop production is a vital element for analyzing the biomass feedstock availability. Neglecting this quantification and BY estimation by cultivar and impact of WS on production will result in reduced biomass feedstock availability to established powerplants which will not only influence overall energy potential (E) but also influence the input cost of energy conversion process due to changes occurred in biomass composition. Cultivar type, the physiological response of a specific cultivar and the conditions of the growing environment also influence biomass composition and BY. Stable and stress-tolerant cultivars with the higher capability to adapt WS are recommended to be cultivated to minimize the crop production risks [24] in this scenario. This is because stress-tolerant cultivars exhibit a relatively stable and higher yield response under a diverse range of environments [25]. Approximately 116 cultivars have been reported under cultivation in different rice-growing areas of Thailand [26]. These cultivars vary in terms of their production potential and physiological characteristics. Farmers in Thailand choose to grow specific cultivars of their choice as they are concerned with the economic part of the plant. Preference for plantation of specific cultivars changes due to production level differences over years. To satisfy local farmer's requirements, it is important to obtain information on cultivar production performance, by cultivar type, growing site and growing conditions including sensitivity to WS. Biomass utilization systems [27] and small biomass-based powerplants need precise biomass feedstock data and a prediction of variability and availability of biomass feedstock for their designing in a specific area. Hence, it becomes important to understand that how WS can impact biomass composition, biomass feedstock availability and may pose a potential threat to established small biomass-based powerplants for sustainable energy generation. Some studies have been conducted for BY estimation for the establishment of biomass-based powerplants, but the authors do not give attention to the cultivar types for their biomass producing potential difference under WW and WS conditions, changes predicted due to farmers choice over time and cultivar failure under WS. Therefore, this study was conducted to determine the impact of WS on the rice biomass productivity, quality, cultivar stability and E of the rice biomass feedstock of Thai lowland rice cultivars. As per the authors' knowledge, this is the first study to investigate the potential impacts of WS and cultivar types on rice biomass composition, quality and biomass feedstock availability to established small biomass-based powerplants.

2. Materials and Methods

2.1. Data Collection

Six commonly available Thai lowland rice cultivars based on popularity among farmers including Hom Nang Kaew (1), Hom Chan (2), Hom Pathum (3), Dum Ja (4), Khao Dawk Mali–105 (5) and RD–15 (6) were assessed in the current study. Data for stem height

(SH), stem numbers (SN) and BY were collected from assessment trials conducted in the field research area (7°00′14.5″ N, 100°30′14.7″ E) of Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla Province, in Southern Thailand (Figure 1) during 2019–2020. Songkhla province is located in the eastern part of Southern Thailand and the climate of Songkhla is characterized by hot or dry season and rainy season. Mean minimum and mean maximum temperature reaches 24.8 °C and 31.5 °C, respectively, with an annual average temperature of 27.9 °C and average annual rainfall of 20166.7 mm [28]. In brief, trials were conducted using a randomized complete block design with three replicates and two treatments including well–watered treatment (WWT) and water-stressed treatment (WST). Plants in WWT received supplementary irrigation throughout the growing period including rainfall; however, plants in WST received only rainfall as irrigation water after tillering stage. Each cultivar was grown in a separate plot with 4 rows of 3-m length. Plants were maintained at 25 cm while rows were distanced at 30 cm. Number of days to 50% maturity (DM) was recorded by counting the number of days from the planting date. SH, SN and BY were recorded at harvest by randomly selecting three plants for each cultivar from each treatment plot. Plant biomass samples were dried in an oven at 70 °C for different time durations until a constant weight was observed to obtain BY on a dry weight basis.

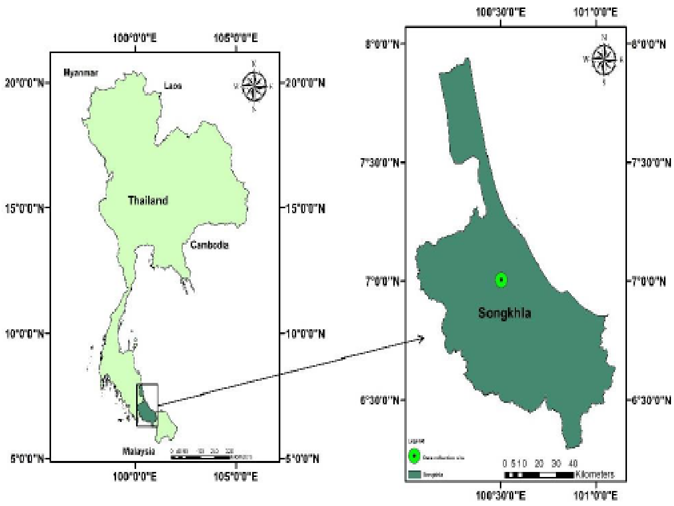

Figure 1. Experimental location in Southern Thailand (Source: Adapted from ArcGIS).

2.2. Biomass Composition Analysis

Oven–dried plant biomass samples were finely ground into 1 mm (grinder model: Retch Cyclone Mill Twister). The ground biomass samples were stored in sealed plastic bags until biomass composition analysis was performed. Biomass composition analysis was performed for proximate contents using a macro thermogravimetric analyzer (model: TGA 701, LECO, USA) at Scientific Equipment Center of Prince of Songkla University, Thailand to examine MC, VM, FC and ash contents. Lignocellulosic analysis was performed by analyzing acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) which were used to compute percentages of cellulose contents (1), hemicellulose contents (2), lignin contents (3) and extractives (4) by following equations. HHV (5) was computed using formulae given by Lozano–García and Parras–Alcántara [29]. Energy conversion [30] for potential energy per hectare area in kilowatt–hour unit (kWh.ha^{-1}) was computed to obtain E by Equation (6) in which C1 is coefficient (3.6 MJ) of conversion of MJ to kWH and C2 is plant conversion efficiency taken as the average of 20% [31].

$$\text{Cellulose contents} = \text{ADF} - \text{ADL} \tag{1}$$

$$\text{Hemicellulose content} = \text{NDF} - \text{ADF} \quad (2)$$

$$\text{Lignin content} = \text{ADL} \quad (3)$$

$$\text{Extractives} = 100 - (\text{Cellulose} + \text{Hemicellulose} + \text{Lignin}) \quad (4)$$

$$\text{HHV} = 0.3536\text{FC} + 0.1559\text{VM} - 0.0078\text{A} \quad (5)$$

$$\text{E} = (\text{HHV}/\text{C1}) \times \text{C2} \times \text{Biomass} \quad (6)$$

$$\text{SSI} = (1\text{–}\text{Ys}/\text{Yw})/\text{D} \quad (7)$$

2.3. Statistical Analysis

Crop data and biomass composition analysis data obtained from experiment and laboratory, respectively, were used separately in statistical program R (version: 2.14.0) to test the significance. A two-way analysis of variance (ANOVA) was performed for DM, SH, SN and BY from three replications with effect to treatments. Mean comparisons were made by using the least significant difference (LSD) and *p-value* <0.05 was considered as significantly different. ANOVA was also performed for biomass composition elements to assess the significance of results and the effect of treatments on biomass composition. Pearson's correlation analysis was conducted for evaluated biomass contributing parameters and energy components. To analyze the stability of rice cultivars for BY, mean BY was used to calculate the measure of biomass production stability and stress susceptibility index (SSI) (7) was computed [32]. Mean relative yield (RY) for comparison under WS was determined as the yield of each cultivar grown in WST divided by the yield of the highest yielded cultivar among six assessed cultivars.

3. Results

3.1. Rice Productivity

There was a highly significant alteration for DM, SH, SN and BY, whereas no significant difference was observed for interactions among cultivars and treatments for BY (Table 1). DM was increased under WS for all cultivars (Figure 2a) and the difference ranged 4–11 days. SH at maturity (Figure 2b) and SN per meter square (Figure 2c) were decreased for all cultivars under WS. SH was decreased by 3–25% under WS for tested cultivars. SN.m^{-2} decreased 2–89% in WST. Biomass (Figure 2d) was reduced by 11–41% in WST. SSI (Table 2) values ranged 0.51–1.97 under WS, whereas RY for biomass under WW, (RYWW) and WS (RYWS) ranged from 0.24 to 1.00 and 0.16 to 1.00, respectively (Table 2). SSI for BY indicated that cultivars 3 and 4 exhibited comparatively smaller reductions in their BY and were found to be stress-tolerant and high-yielding for biomass production.

Table 1. Mean squares of analysis of variance for days to maturity, stem height, stem numbers and biomass yield of six lowland rice cultivars.

SOV	df	Days to Maturity	Stem Height	Stem Number	Biomass Yield
Replications	2	5.44	69.75	917.33	0.77
Cultivars	5	2224.18 ***	7699.20 ***	1996.47 ***	205.00 ***
Treatments	1	498.78 ***	5088.44 ***	9604.00 ***	59.75 ***
Cultivars × Treatments	5	14.44 ***	356.11 ***	2347.93 ***	2.05 ns
Error	22	2.23	78.02	215.24	2.06
CV %		1.04	6.42	9.67	12.88

SOV = source of variation, df = degree of freedom, *** = highly significant ($p < 0.001$), ns = non-significant.

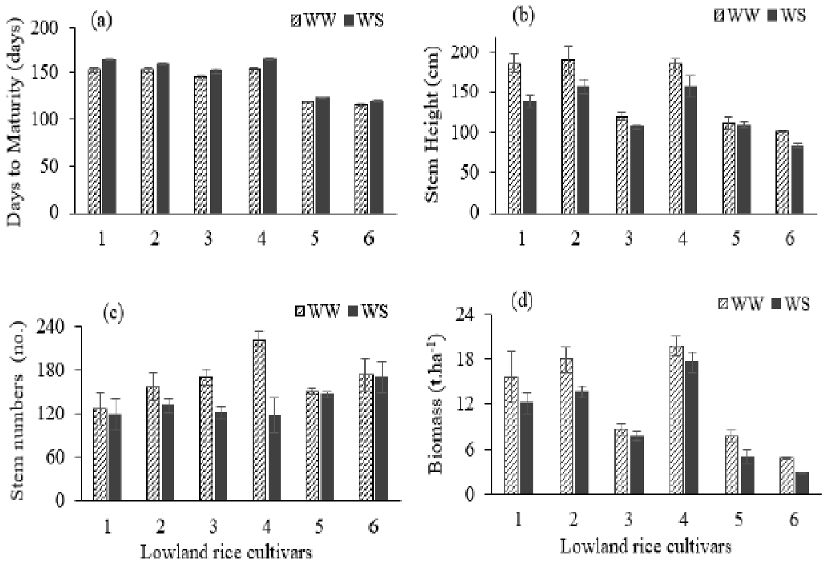

Figure 2. Days to maturity (**a**), stem height (**b**), stem numbers (**c**) and biomass yield (**d**) for six lowland rice cultivars under well−watered (WW) and water−stressed (WS) conditions. Vertical bars refer to ± standard errors for average data from three replicates.

Table 2. Stress susceptibility index (SSI) and relative yield (RY) for biomass yield in six lowland rice cultivars.

	Cultivars	Well−Watered		Water−Stressed		
		BY ± SE	**RYWW**	**BY ± SE**	**SSI**	**RYWS**
1	Hom Nang Kaew	15.66 ± 1.99	0.79	12.18 ± 0.81	1.07	0.69
2	Hom Chan	17.96 ± 0.99	0.91	13.70 ± 0.48	1.14	0.78
3	Hom Pathum	8.70 ± 0.44	0.44	7.75 ± 0.31	0.53	0.44
4	Dum Ja	19.72 ± 0.74	1.00	17.61 ± 0.81	0.51	1.00
5	Khao Dawk Mali−105	7.76 ± 0.41	0.39	5.05 ± 0.52	1.68	0.29
6	RD−15	4.81 ± 0.08	0.24	2.84 ± 0.05	1.97	0.16
	Mean	12.43	0.63	9.86	−	0.56

BY = mean biomass yield; ± SE = standard error, SSI = stress susceptibility index; RYW = relative yield under well−watered conditions; RYWS = relative yield under water−stressed conditions.

3.2. *Biomass Composition and Energy Contents*

Statistical comparisons for proximate contents (Table 3) indicated a highly significant difference among MC, VM, FC, ash, HHV and E for cultivars, treatments as well as their interactions except for a non-significant difference for VM under treatment and for FC under cultivar as well as the interaction of cultivar and treatments. MC (Figure 3a) were higher for cultivars 1, 2, 3, 4 and 5 by 5, 2, 14, 4 and 3%, whereas they were decreased for cultivar 6 by 4%, respectively, when compared with WST in proximate analysis. VM (Figure 3b) was increased for cultivars 1 and 3 by 2% whereas decreased for cultivars 4 and 6 by 2%, however no change was observed for cultivars 2 and 5. Composition analysis indicated that FC contents were between 15 and 16% and values ranged between 15.52–16.00 for WWT and 15.14–15.69 for WST, respectively. FC contents (Figure 3c) were increased for cultivar 1 by 1% whereas they were decreased for cultivars 3, 4 and 6 by 3, 4 and 5%, respectively, and no change was observed for cultivars 2 and 5. Ash contents (Figure 3d) were increased for cultivars 2, 4 and 6 by 4, 22 and 29%, whereas they were decreased for cultivars 1, 3 and 5 by 15, 17 and 4%, respectively. HHV was increased for cultivars 1 and 3 by 2%, whereas it was decreased for cultivars 4 and 6 by 2 and 3%, respectively, whereas no significant change was observed for cultivars 2 and 5.

Table 3. Mean squares of analysis of variance of proximate analysis, HHV and potential bioenergy € for six lowland rice cultivars.

SOV	df	MC	VM	FC	Ash	HHV	E
R	2	0.011	0.037	0.062	0.001	0.001	331007
C	5	0.965 ***	5.524 ***	0.119 ns	5.200 ***	0.149 ***	84120000 ***
T	1	0.528 ***	0.139 ns	0.686 *	0.232 ***	0.008 **	24310000 ***
C × T	5	0.206 ***	1.455 ***	0.157 ns	3.444 ***	0.046 ***	834913 ns
Error	22	0.001	0.139	0.121	0.006	0.002	818514
CV %		0.57	0.54	2.23	0.98	0.41	12.82

SOV = source of variation, df = degree of freedom, R = replications, C = cultivars, T = treatments, MC = moisture contents, VM = volatile matter, FC = fixed carbon, HHV = higher heating value, E = Potential bioenergy, *** = highly significant ($p < 0.001$), ** = moderately significant ($p < 0.01$), * = significant ($p < 0.05$), ns = non-significant.

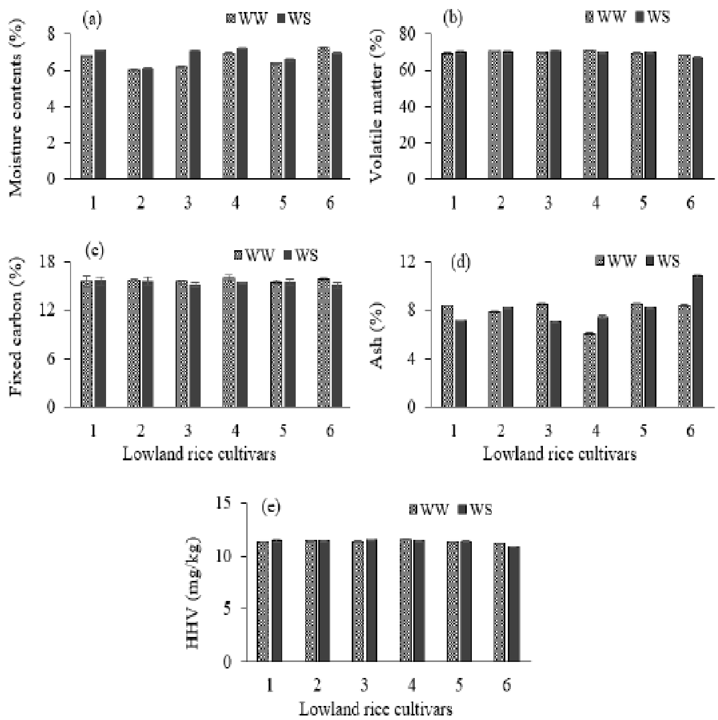

Figure 3. Proximate contents including moisture contents (**a**), volatile matter (**b**), fixed carbon contents (**c**) ash contents (**d**) and higher heating value (**e**) for six lowland rice cultivars in well−watered (WW) and water−stressed (WS) conditions. Vertical bars refer to ± standard errors for average data from three replicates.

3.3. Impact of WS on Lignocellulosic Properties

There was a highly significant difference (Table 4) for cellulose, hemicellulose, lignin and extractives for cultivars, treatments and their interactions and a non-significant difference for hemicellulose under treatments. Cellulose contents (Figure 4a) were increased for cultivars 1, 3 and 6 by 4, 16 and 3%, whereas they were decreased for cultivars 2 and 5 by 4 and 1%, respectively, whereas no change was observed for cultivar 4 under WS. Hemicellulose contents (Figure 4b) were increased for cultivars 1, 2, and 3 by 3, 6 and 10% whereas they were decreased for cultivars 4, 5 and 6 by 1, 3 and 12%, respectively, under WS. Lignin contents (Figure 4c) were increased for cultivars 1, 3, 4 and 6 by 9, 39, 9 and 7%, whereas they were decreased for cultivars 2 and 5 by 2 and 3%, respectively, under WS. Extractives (Figure 4d) were increased for cultivars 5 and 6 by 3 and 7%, whereas they were decreased for cultivars 1, 2 and 3 by 5, 1 and 21%, respectively, whereas no change was observed for cultivar 4 under WS.

Table 4. Mean squares of analysis of variance of lignocellulosic analysis of six lowland rice cultivars.

SOV	df	Cellulose	Hemicellulose	Lignin	Extractives
R	2	0.012	0.016	0.006	0.003
C	5	5.606 ***	6.562 ***	0.039 ***	16.708 ***
T	1	7.471 ***	0.043 ^{ns}	0.777 ***	14.618 ***
C × T	5	6.304 ***	6.733 ***	0.300 ***	22.527 ***
Error	22	0.050	0.052	0.002	0.008
CV %		0.730	0.860	1.360	0.220

SOV = source of variation, df = degree of freedom, R = replications, C = cultivars, T = treatments, CV = coefficient of variation, *** = highly significant ($p < 0.001$), ns = non-significant.

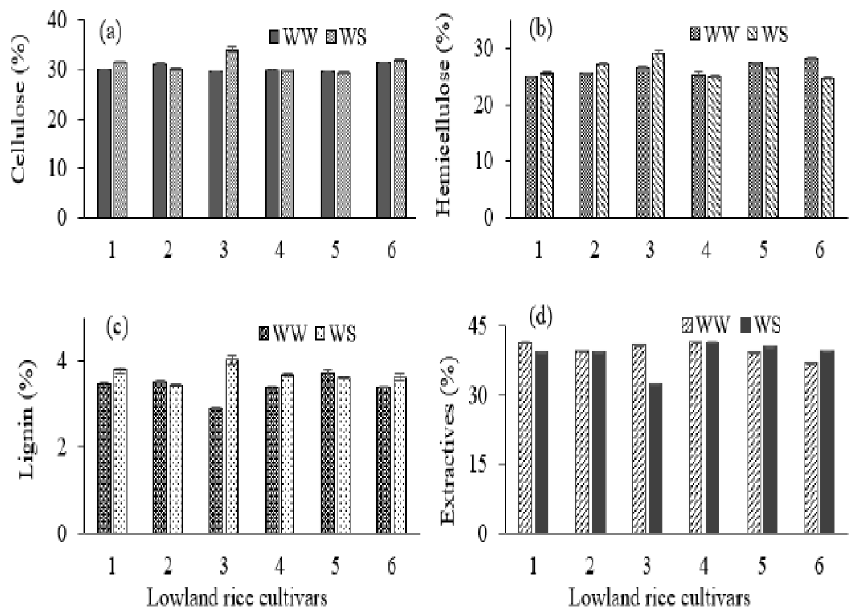

Figure 4. Cellulose (**a**), Hemicellulose (**b**), Lignin (**c**) and Extractives (**d**) percentages for six lowland rice cultivars in well–watered (WW) and water–stressed (WS) conditions. Vertical bars refer to ± standard errors for average data from three replicates.

3.4. Energy Potential (E)

E, which depends upon HHV as well as biomass production and composition, was significantly different (Table 3) due to the effect of cultivar type and water treatments except by the interaction between the cultivar type and treatments for all cultivars evaluated. All cultivars exhibited a higher potential for bioenergy under WW conditions (Figure 5). Values ranged between 2990 and 12,685 kWh.ha^{-1} for WWT and 1724 and 11,142 kWh.ha^{-1} for WST, respectively (Figure 5). Maximum bioenergy potential was achieved by cultivar 6 due to higher biomass production. E was reduced under WS for all cultivars including cultivar 1, 2, 3, 4, 5 and 6 by 21%, 24%, 10%, 12%, 35% and 42%, respectively (Figure 5).

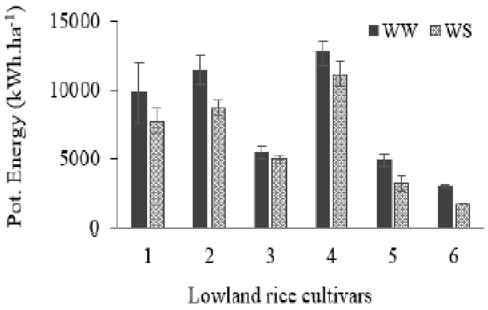

Figure 5. Potential bioenergy per hectare from biomass of lowland rice cultivars in well−watered (WW) and water−stressed (WS) conditions. Vertical bars refer to ± standard errors for average data from three replicates.

3.5. Correlation Study

SN were significantly ($p < 0.05$) negative, whereas SH and BY were highly significant ($p < 0.001$) and positively correlated with DM (Table S1). SH was also highly significant ($p < 0.001$) and positively associated with BY (Table S1).

Correlation for proximate components indicated a highly significant ($p < 0.001$) positive association among HHV, BY, E and VM, whereas a highly significant ($p < 0.001$) negative association was observed between ash contents and VM (Table S2). Significant ($p < 0.05$) positive correlation among BY, E and FC was observed, whereas a significantly ($p < 0.05$) negative association among ash contents and FC was observed (Table S2). Ash contents were highly significant ($p < 0.001$) and negatively correlated with HHV, BY and E (Table S2). Highly significant ($p < 0.001$) and positive association was observed among BY, HHV and E (Table S2).

Correlation analysis for lignocellulosic properties resulted in a highly significant ($p < 0.001$) positive association among cellulose hemicellulose and lignin contents (Table S3), whereas cellulose, hemicellulose and lignin were significantly ($p < 0.001$) negatively correlated (Table S3).

4. Discussion

WS affected biomass production performance of all cultivars. Maturity duration was delayed under WS. SH and SN was decreased for all cultivars under WS. Davatgar et al. [33] and Hussain et al. [34] observed that WS caused a significant decline in SH of rice cultivars. SH was negatively correlated with WS. Reduction in SH occurs as the reduced water supply under WS limits the cell elongation which results in a reduction in internode length [35]. Higher SH and more SN contributed to an increase in plant biomass. Furthermore, SH had a significant positive correlation with BY. Knoll et al. [36] also observed that mature SH was highly correlated with biomass yield. Reduction in SH and SN under WS resulted in a reduction in plant biomass. Zain et al. [37] reported that GY, biomass, filled spikelet, and SH were reduced under the increased duration of WS intervals. Increased WS also decreased the plant morphology and rice yield production in a study conducted by Zulkarnain et al. [38]. Cultivars 3 and 4 exhibited comparatively smaller reductions in their BY maintaining plant performance under WS which exhibited their stress tolerance capability. Bruckner and Frohberg [39] stated that cultivars with low SSI values, (less than 1) could be considered stress-tolerant cultivars as they showed comparatively smaller reductions in yield under WS conditions when compared with WW. RY was taken into consideration as RY gives the measure of relatively lower or higher yield under WS conditions. Cultivars 3 and 4 were found to be stress-tolerant as well as relatively high yielding for biomass production. Bouman and Tuong [40] also stated that tolerant cultivars maintained their yields as they maintained higher plant physiological processes and recovery of plant functions following WS. Hence, it was observed that cultivation of stress-tolerant, as well as high-yielding cultivars, will sustain the biomass feedstock availability rather than stress-susceptible cultivars.

The proximate composition of biomass of all cultivars was altered. According to Obernberger and Thek [41], MC may vary significantly, and it is an undesired component of any type of fuel. MC also influence the heating values, combustion temperatures as well as combustion efficiencies. Higher MC in biomass release lower net heating values; therefore, low MC are desired in biomass for energy applications. Results indicated that MC were increased when biomass samples were used from WST resulting in a negative impact on biomass quality. VM is a desired component in biomass and according to Demirbas [42] and Vassilev et al. [43], and it usually comprises CO, CO_2, H_2, MC, and tars. Depending upon raw materials, generally, biomass contains higher VM ranging from 75% to 90% [44]. VM was found to have a significant positive correlation with HHV, BY and E while having a significant correlation with ash. Higher ash contents resulted in lower VM. Kreil and Broekema [45] stated that in a combustion system, FC produces char and it is burnt as a solid substance and higher FC results in a positive impact on the combustion process. According to Yang et al. [46], FC contents should be expected at the range 7–20%. In this study, composition analysis indicated that FC contents were between 15 and 16%. FC was negatively correlated with ash whereas it was in positive correlation with BY and E. Ash is considered as incombustible matter in biomass, which is not only an undesirable material, but also higher ash contents result in high carbon and gas emissions. Ash was negatively correlated with HHV, BY and E. Another important factor is "Slag" formation in boilers or furnaces during the combustion process which results because of the lower melting point of ash in thermal processing. Hodgson et al. stated that slag formation in boilers or furnaces hinders the energy conversion and combustion efficiency is decreased [47]. Results indicated that although cultivars 2 and 4 were stress-tolerant and maintained their BY, their biomass quality was affected as ash contents were increased, which is an undesired attribute. Results exhibited that cultivation of such cultivars over time or due to farmer's preference and occurrence of WS will not only impact biomass quantity but will also impact the biomass quality. An increase in ash contents of specific cultivars under WS indicted that biomass obtained from these cultivars will produce more ash, limiting the combustion efficiency. Heating values are considered as energy contents of fuel as standard which is usually described as lower heating value or HHV. HHV was positively correlated with VM while negatively correlated with ash. Voca et al. [48] found that there was no significant difference observed for the HHV of Plum and it is possible that different cultivars may exhibit similar HHV. Heating values also depend upon the concentration of FC, VM and ash. According to Shrivastava et al. [49] biomass containing higher FC, VM and low ash contents will deliver higher heating values. Cultivar 2, 4 and 6 indicated that ash contents were increased while remaining proximate properties were decreased under WS. This indicated that WS influenced the biomass development and proximate composition which ultimately influenced heating values. Results supported the hypothesis that biomass obtained from cultivation of such types of cultivars over time and WS may influence the heating potential of rice biomass.

WS caused the variations in lignocellulosic response for all cultivars. During the energy conversion process, higher levels of cellulose and hemicellulose and low levels of lignin and extractives are desired. We found that WS increased the levels of lignin and extractives for cultivars 1, 3, 4 and 6 whereas it decreased cultivars 2 and 5. Although cellulose for cultivar 6 and cellulose and hemicellulose for cultivars 1 and 3 were increased, it is a point of concern that an increase in lignin contents will require higher energy input during the energy conversion process. Cultivar 4 maintained the concentration of cellulose and hemicellulose under WS despite the increase in lignin and extractives. Cultivars with higher cellulose and hemicellulose concentration in their biomass will be able to exhibit higher energy potential. Palamanit et al. [50] found that during pyrolysis, the biomass with higher levels of cellulose as well as hemicellulose contents promoted comparatively greater yields of bio-oil and liquid than the biomass with higher lignin contents. It is due to this reason that thermal disintegration and conversion of cellulose and hemicellulose is much easier than lignin. Kim et al. [51] also stated that biomass containing higher cellulose and hemicellulose contents produced higher bio-oil yield. The current results indicated that an increase in lignin contents of biomass produced under WS will impact the quality of energy output. In addition, it could be that the reduction in hemicellulose of cultivar 6 may not affect energy output as cellulose concentration was increased. This is similar to Qu et al. [52], who also found that cellulose provided a high bio-oil yield during pyrolysis because cellulose is comparatively more volatile as compared to hemicellulose. However, cellulose and hemicellulose alone cannot predict and constitute the energy output from a specific area grown as the concentration of these components is computed with the produced biomass.

Energy potential (E) is dependent upon HHV, BY and biomass composition. Higher E was achieved under WW conditions by all cultivars, and it was significantly reduced under WS conditions (Figure 5). E was also positively correlated with FC, VM, HHV and BY, whereas it was negatively associated with ash contents (Table S2). The results indicated that higher biomass-producing cultivars would generate higher E and reduction in biomass yield will negatively impact the energy potential. Maximum E was achieved by cultivar 6 due to higher biomass production. Ambrosio et al. [30] also found that higher bioenergy potential was associated with higher biomass production and HHV. Biomass productivity is dependent upon crop growing conditions, planting density, fertilizer and nutrient availability, crop management practices and climatic factors which can limit biomass production. In a crop management study, it was observed that the heating value and the potential for energy for power generation from maize crop along with dry matter productivity and grain production was increased by nitrogen fertilizer application while it was slightly influenced by inter-row spacing [30]. Cultivation of low-biomass-producing cultivars over time, or by farmer choice for grains, will also negatively impact biomass availability to biomass-based powerplants. In this study, although some cultivars, e.g., cultivar 4, exhibited smaller reductions in BY under WS and rice fields grown with such cultivars will be able to contribute higher bioenergy, the results indicated the potential decline in biomass feedstock availability, biomass quality and overall energy output if WS or drought occurs during the growing season.

5. Conclusions

This study revealed that WS resulted in a negative impact on all cultivars' performance affecting the biomass composition, and hence the quality, and biomass feedstock availability. Cultivars Hom Pathum and Dum Ja were found to be stress-tolerant as they exhibited smaller reductions in their BY under WS indicating that cultivation of stress-tolerant cultivars will help to stabilize BY and feedstock availability as compared to susceptible cultivars. The proximate composition of biomass of all cultivars was altered and the quality of biomass of cultivars Hom Chan, Dum Ja and RD-15 was lowered due to an increase in ash contents. Lignin and extractives which are undesired in higher concentrations were also increased under WS for most cultivars. E, which is dependent upon HHV and biomass production potential, was decreased 10–42% under WS. It was concluded that E will be affected if low biomass-yielding, stress-susceptible cultivars are grown, WS occurs, or farmers continue to grow specific cultivars. In such a case, biomass availability will be reduced to established small biomass-based power plants along with lowered biomass quality, resulting in a decline in final energy potential.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su131810449/s1, Table S1: Combined Pearson's correlation coefficients matrix for days to maturity, stem height, stem numbers and biomass yield, Table S2: Combined Pearson's correlation coefficients matrix for moisture contents (MC), volatile matter (VM), fixed carbon (FC), ash, higher heating value (HHV), biomass yield (BY) and energy potential (E), Table S3: Combined Pearson's correlation coefficients matrix for lignocellulosic components.

Author Contributions: N.H. conceived and conceptualized the idea. N.H. and T.H. performed the literature review. M.A. and S.D. provided technical expertise to strengthen the basic idea. T.H. helped in the collection of data and its analysis. J.T., acquired funds, proofread and provided intellectual guidance along with M.A. and S.D. All authors read the first draft, helped in revision and approved the article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Faculty of Engineering, Prince of Songkla University and Graduate School, Prince of Songkla University with Graduate School thesis research funding for topics on community problem solving.

Acknowledgments: Authors are thankful to anonymous reviewers for providing valuable comments. We would like to thank Sobia Ikram, researcher, School of Medical and Applied Sciences, Central Queensland University, Australia for her help in R program.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cuiping, L.; Yanyongjie; Chuangzhi, W.; Haitao, H. Study on the distribution and quantity of biomass residues resource in China. *Biomass Bioenergy* **2004**, *27*, 111–117. [CrossRef]
2. Stone, K.C.; Hunt, P.G.; Cantrell, K.B.; Ro, K.S. The potential impacts of biomass feedstock production on water resource availability. *Bioresour. Technol.* **2010**, *101*, 2014–2025. [CrossRef] [PubMed]
3. Suzane, T.; Regina, D.; Savioli, M.; Maria, S.; Garcia, R. Sugarcane straw as a potential second generation feedstock for biorefinery and white biotechnology applications. *Biomass Bioenergy* **2021**, *144*, 105896. [CrossRef]
4. Hashem, M.; Ali, E.H.; Abdel-Basset, R. Recycling rice straw into Biofuel "ethanol" by Saccharomyces cerevisiae and Pichia guilliermondii. *J. Agric. Sci. Technol.* **2013**, *15*, 709–721.
5. Varvel, G.E.; Wilhelm, W.W. Cob Biomass Production in the Western Corn Belt. *BioEnergy Res.* **2008**, *1*, 223–228. [CrossRef]
6. Healy, M.; Toupin, K. Biofuel Conversion–First Step-Fuel Selection. In Proceedings of the Clearwater Clean Coal Conference, Clearwater, FL, USA, 6–10 June 2010.
7. Lim, J.S.; Manan, Z.A.; Alwi, S.R.W.; Hashim, H. A review on utilisation of biomass from rice industry as a source of renewable energy. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3084–3094. [CrossRef]
8. Cheewaphongphan, P.; Junpen, A.; Kamnoet, O.; Garivait, S. Study on the potential of rice straws as a supplementary fuel in very small power plants in Thailand. *Energies* **2018**, *11*, 270. [CrossRef]
9. Alternative Energy and Efficiency Information Center. *Thailand Alternative Energy Situation*; Alternative Energy and Efficiency Information Center, Department of Alternative Energy Development and Efficiency, Ministry of Energy: Bangkok, Thailand, 2015; pp. 1–57.
10. Wang, W.; Porninta, K.; Aggarangsi, P.; Leksawasdi, N.; Li, L.; Chen, X.; Zhuang, X.; Yuan, Z.; Qi, W. Bioenergy development in Thailand based on the potential estimation from crop residues and livestock manures. *Biomass Bioenergy* **2021**, *144*, 105914. [CrossRef]
11. Barz, M.; Delivand, M.K. Agricultural Residues as Promising Biofuels for Biomass Power Generation in Thailand. *J. Sustain. Energy Environ. Spec. Issue* **2011**, 21–27.
12. Office of Agricultural Economics (OAE). *Agricultural Statistics of Thailand*; Ministry of Agriculture and Cooperatives: Bangkok, Thailand, 2016; p. 206.
13. Monkham, T.; Jongdee, B.; Pantuwan, G.; Mitchell, J.H.; Sanitchon, J.; Fukai, S. 517 Responses of rainfed lowland rice genotypes to terminal drought in Northeast Thailand. *Khon Kaen Agric. J.* **2016**, *44*, 517–526.
14. Venuprasad, R.; Lafitte, H.R.; Atlin, G.N. Response to direct selection for grain yield under drought stress in rice. *Crop Sci.* **2007**, *47*, 285–293. [CrossRef]
15. Saxena, R.C.; Adhikari, D.K.; Goyal, H.B. Biomass-based energy fuel through biochemical routes: A review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 167–178. [CrossRef]
16. Imam, T.; Capareda, S. Characterization of bio-oil, syn-gas and biochar from switchgrass pyrolysis at various temperatures. *J. Anal. Appl. Pyrolysis.* **2012**, *93*, 170–177. [CrossRef]
17. Antongiovanni, M.; Sargentini, C. Variability in chemical composition of straws. *Option Méditérranéennes* **1991**, *16*, 49–53.
18. van de Velden, M.; Baeyens, J.; Brems, A.; Janssens, B.; Dewil, R. Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction. *Renew. Energy* **2010**, *35*, 232–242. [CrossRef]
19. Garrote, G.; Domínguez, H.; Parajó, J.C. Autohydrolysis of corncob: Study of non-isothermal operation for xylooligosaccharide production. *J. Food Eng.* **2002**, *52*, 211–218. [CrossRef]
20. Saha, B.C. Hemicellulose bioconversion. *J. Ind. Microbiol. Biotechnol.* **2003**, *30*, 279–291. [CrossRef]
21. Yang, H.; Yan, R.; Chen, H.; Lee, D.H.; Zheng, C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel* **2007**, *86*, 1781–1788. [CrossRef]
22. Al-Hakimi, A.M.A. Counteraction of drought stress on soybean plants by seed soaking in salicylic acid. *Int. J. Bot.* **2006**, *2*, 421–426. [CrossRef]

23. Emerson, R.; Hoover, A.; Ray, A.; Lacey, J.; Cortez, M.; Payne, C.; Karlen, D.; Birrell, S.; Laird, D.; Kallenbach, R.; et al. Drought effects on composition and yield for corn stover, mixed grasses, and Miscanthus as bioenergy feedstocks. *Biofuels* **2014**, *5*, 275–291. [CrossRef]
24. Manickavelu, A.; Nadarajan, N.; Ganesh, S.K.; Gnanamalar, R.P.; Babu, R.C. Drought tolerance in rice: Morphological and molecular genetic consideration. *Plant Growth Regul.* **2006**, *50*, 121–138. [CrossRef]
25. Anantha, M.S.; Patel, D.; Quintana, M.; Swain, P.; Dwivedi, J.L.; Torres, R.O.; Verulkar, S.B.; Variar, M.; Mandal, N.P.; Kumar, A.; et al. Trait combinations that improve rice yield under drought: Sahbhagi Dhan and new drought-tolerant varieties in South Asia. *Crop Sci.* **2016**, *56*, 408–421. [CrossRef]
26. Rice Department-Ministry of Agriculture and Cooperatives. Rice Knowledge Bank: Rice Cultivate Species. Available online: http://www.ricethailand.go.th/Rkb/varieties/index.php-file=content.php&id=1.htm (accessed on 8 January 2017).
27. Summers, M.D.; Jenkins, B.M.; Hyde, P.R.; Williams, J.F.; Mutters, R.G.; Scardacci, S.C.; Hair, M.W. Biomass production and allocation in rice with implications for straw harvesting and utilization. *Biomass Bioenergy* **2003**, *24*, 163–173. [CrossRef]
28. TMD. Climatological Center, Thai Meteorological Department Report. 2021. Available online: http://climate.tmd.go.th/ (accessed on 19 August 2021).
29. Lozano-García, B.; Parras-Alcántara, L. Short-term effects of olive mill by-products on soil organic carbon, total N, C: N ratio and stratification ratios in a Mediterranean olive grove. *Agric. Ecosyst. Environ.* **2013**, *165*, 68–73. [CrossRef]
30. Ambrosio, R.; Pauletti, V.; Barth, G.; Povh, F.P.; da Silva, D.A.; Blum, H. Energy potential of residual maize biomass at different spacings and nitrogen doses. *Ciência Agrotecnologia* **2017**, *41*, 626–633. [CrossRef]
31. Nogueira, L.A.H.; Lora, E.E.S. *Dendroenergia: Fundamentos e Aplicações*, 2nd ed.; Interciência: Rio de Janeiro, Brazil, 2003; p. 200.
32. Fischer, R.A.; Maurer, R. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Aust. J. Agric. Res.* **1978**, *29*, 897–912. [CrossRef]
33. Davatgar, N.; Neishabouri, M.R.; Sepaskhah, A.R.; Soltani, A. Physiological and morphological responses of rice (Oryza sativa L.) to varying water stress management strategies. *Int. J. Plant Prod.* **2009**, *3*, 19–32. [CrossRef]
34. Hussain, T.; Anothai, J.; Nualsri, C.; Soonsuwon, W. Application of CSM-CERES-Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield. *Indian J. Agric. Res.* **2018**, *52*, 140–145. [CrossRef]
35. Patel, D.P.; Das, A.; Munda, G.C.; Ghosh, P.K.; Bordoloi, J.S.; Kumar, M. Evaluation of yield and physiological attributes of high-yielding rice varieties under aerobic and flood-irrigated management practices in mid-hills ecosystem. *Agric. Water Manag.* **2010**, *97*, 1269–1276. [CrossRef]
36. Knoll, J.E.; Anderson, W.F.; Missaoui, A.; Hale, A.; Hanna, W.W. Biomass production and stability of five energycane cultivars at two latitudes in Georgia. *Agrosyst. Geosci. Environ.* **2021**, *4*, 1–14. [CrossRef]
37. Zain, N.A.M.; Ismail, M.R.; Puteh, A.; Mahmood, M.; Islam, M.R. Impact of cyclic water stress on growth, physiological responses and yield of rice (*Oryza sativa* L.) grown in tropical environment. *Ciência Rural.* **2014**, *44*, 2136–2141. [CrossRef]
38. Zulkarnain, W.M.; Ismail, M.R.; Ashrafuzzaman, M.; Saud, H.M.; Haroun, I.C. Rice growth and yield under rain shelter house as influenced by different water regimes. *Int. J. Agric. Biol.* **2009**, *11*, 566–570.
39. Bruckner, P.L.; Frohberg, R.C. Stress Tolerance and Adaptation in Spring Wheat 1. *Crop Sci.* **1987**, *27*, 31–36. [CrossRef]
40. Tuong, T.P.; Bouman, B.A.M. Field water mangement to save water and increase its productivity in irrigated lowland rice. *Agric. Water Manag.* **2000**, *1615*, 1–20.
41. Obernberger, I.; Thek, G. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behavior. *Biomass Bioenergy* **2004**, *27*, 653–669. [CrossRef]
42. Demirbas, A. Combustion characteristics of different biomass fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230. [CrossRef]
43. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G. An overview of the chemical composition of biomass. *Fuel* **2010**, *89*, 913–933. [CrossRef]
44. Khan, A.A.; de Jong, W.; Jansens, P.J.; Spliethoff, H. Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Process. Technol.* **2009**, *90*, 21–50. [CrossRef]
45. Kreil, K.; Broekema, S. *Chemical and Heat Value Characterization of Perennial Herbaceous Biomass Mixtures*; Analysis Report; Microbeam Technologies: Grand Forks, ND, USA, 2010.
46. Yang, Y.B.; Ryu, C.; Khor, A.; Yates, N.E.; Sharifi, V.N.; Swithenbank, J. Effect of fuel properties on biomass combustion. Part II. Modelling approach—Identification of the controlling factors. *Fuel* **2005**, *84*, 2116–2130. [CrossRef]
47. Hodgson, E.M.; Fahmi, R.; Yates, N.; Barraclough, T.; Shield, I.; Allison, G.; Bridgwater, A.V.; Donnison, I.S. Miscanthus as a feedstock for fast-pyrolysis: Does agronomic treatment affect quality? *Bioresour. Technol.* **2010**, *101*, 6185–6191. [CrossRef]
48. Voća, N.; Bilandžija, N.; Jurišić, V.; Matin, A.; Krička, T.; Sedak, I. Proximate, ultimate, and energy values analysis of plum biomass by-products case study: Croatia's potential. *J. Agric. Sci. Technol.* **2016**, *18*, 1655–1666.
49. Shrivastava, P.; Kumar, A.; Tekasakul, P.; Lam, S.S.; Palamanit, A. Comparative investigation of yield and quality of bio-oil and biochar from pyrolysis of woody and non-woody biomasses. *Energies* **2021**, *14*, 1092. [CrossRef]
50. Palamanit, A.; Khongphakdi, P.; Tirawanichakul, Y.; Phusunti, N. Investigation of yields and qualities of pyrolysis products obtained from oil palm biomass using an agitated bed pyrolysis reactor. *Biofuel Res. J.* **2019**, *6*, 1065–1079. [CrossRef]
51. Kim, S.S.; Ly, H.V.; Kim, J.; Choi, J.H.; Woo, H.C. Thermogravimetric characteristics and pyrolysis kinetics of Alga Sagarssum sp. *biomass. Bioresour. Technol.* **2013**, *139*, 242–248. [CrossRef]
52. Qu, X.; Liang, P.; Wang, Z.; Zhang, R.; Sun, D.; Gong, X.; Gan, Z.; Bi, J. Pilot Development of Polygeneration Process of Circulating Fluidized Bed Combustion combined with Coal Pyrolysis. *Chem. Eng. Technol.* **2011**, *34*, 61–68. [CrossRef]

VITAE

Name Mrs. Nurda Hussain

Student ID 6310120017

Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Science (Biology)	Prince of Songkla University	2017
Master of Engineering (Energy Technology)	Prince of Songkla University	2022

Scholarship Awards during Enrolment

- Scholarship award for master's degree from Faculty of Engineering Prince of Songkla University
- Graduate School thesis research funding for topic on community problem solving

List of Publications

Hussain, T., **Hussain, N.**, Ahmed, M. Nualsri, C. and Duangpan, S. 2022. Impact of Nitrogen Application Rates on Upland Rice Performance, Planted under Varying Sowing Times. *Sustainability*. 14: 1997. *doi: 10.3390/su14041997*. Q1. Impact Factor: 3.251.

Hussain, T., Gollany, H.T., **Hussain, N.**, Ahmed, M. Tahir, M. and Duangpan, S. 2022. Synchronizing Nitrogen Fertilization and Planting Date to Improve Nitrogen Use Efficiency, Productivity and Profitability of Upland Rice. *Frontiers in Plant Science*. 13: 895811. *doi:10.3389/fpls.2022.895811*. Q1. Impact Factor: 5.753.

Hussain, N., Ahmed, M., Duangpan, S., Hussain, T., Taweekun, J. 2021. Potential Impacts of Water Stress on Rice Biomass Composition and Feedstock Availability for Bioenergy Production. *Sustainability*. 13: 10449. *doi:10.3390/su131810449*. Q1. Impact Factor: 3.251.

Hussain, T., **Hussain, N.**, Ahmed, M. Nualsri, C. and Duangpan, S. 2021. Responses of Lowland Rice Genotypes under Terminal Water Stress and Identification of Drought Tolerance to Stabilize Rice Productivity in Southern Thailand. *Plants*. 10: 2565. *doi: 10.3390/plants10122565*. Q1. Impact Factor: 3.935.