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Effect of Combined Fertilizer and Rice Husk Biochar on Rice Yield, Nitrogen Content, Grain Quality and Water Productivity under Aerobic Rice Cultivation in Hungary

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1. INTRODUCTION AND OBJECTIVES

Rice is a staple food for more than half of the world’s population (Baruah et al., 2016). It provides an excellent source of nutrients, carbohydrates, protein, and energy to our body (Sharada & Sujathamma, 2018). The quality of rice depends on the nutrients available in the soil and fertilizers are usually applied to improve the soil productivity hence increase crop production. Chemical or inorganic fertilizers are frequently used in the field because they can be found easily in the market. However, continuous application of inorganic fertilizer and the excessive use of it was found to negatively affect the environment, decreased soil productivity, reduced soil pH and nitrogen use efficiency, which in turn affecting crop yield and soil health in the long term (Anisuzzaman et al., 2021; Baclayon & Escasinas, 2016; Guo et al., 2022; Kai et al., 2020; Kakar et al., 2020; Liu et al., 2021a; Moe et al., 2019).

On the other hand, organic fertilizers help to maintain soil health and environment as it is rich in organic matter, humus, and beneficial microorganisms (Ghosh & Devi, 2019; Liu et al., 2021a). Many studies have revealed the benefits of organic materials and agricultural by-products to improve soil properties using materials such as plant wastes, kitchen waste, sugarcane bagasse, grasses, rice water, poultry manure, cow urine, compost, and rice husk biochar (Baclayon & Escasinas, 2016; Baruah et al., 2016; Bilkis et al., 2017; Cao et al., 2021; Dobermann & Fairhurst, 2000; Ghosh & Devi, 2019; Guo et al., 2022; Havlin & Heiniger, 2020; Indhirajith et al., 2021). Recognizing the importance of animal manure in crop production, farmers have used them as an important nitrogen substitute source for inorganic fertilizer in crop production (Moe et al., 2019). Similarly, rice husk biochar (RHB) is seen as a promising soil ameliorant to enhance soil properties, utilizing the waste products from rice – the rice hulls. Produced by low thermal degradation under oxygen-depleted conditions, RHB was reported to help improve soil aeration, structure, nutrient availability, and microbial activities, as well as enhanced water-holding capacity and stabilized soil organic matter (Ebe & Ano, 2020; Cao et al., 2021; Nair et al., 2017; Zhaoxiang et al., 2020). In Hungary, rice hull is often un-utilized and serve as a waste. Besides utilizing these waste products to improve soil productivity, it could also help the nation to save energy production by reducing fuels required to produce chemical fertilizers.

However, applying organic fertilizer alone may prolong the rate of nutrients release in the soil. Concerning this, partial replacement of inorganic fertilizers with organic fertilizers will help the

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uptake of both the available nutrients and total nutrients, which then improves soil properties and health (Liu et al., 2021a). Plants primarily require nutrients obtained from the soil in the form of inorganic, organic, and biofertilizers (Havlin & Heiniger, 2020). Studies have shown that the integrated use of inorganic fertilizers with organic resources has resulted in high rice yield (Ahmad et al., 2016; Arif et al., 2014). The combination of these fertilizers has been widely recommended to sustain agricultural production of the degraded soil fertility and quality in Asia and Africa (Ge et al., 2010). It aids to improve soil properties, nutrient usage efficiency, provide essential nutrients to the soil, and increases microbial activity of the soil, leading to improving rice yield (Anisuzzaman et al., 2021; Bilkis et al., 2017; Ghosh & Devi, 2019; Kakar et al., 2020; Liu et al., 2021a).

Until today, water management in rice cultivation is crucial considering declining freshwater availability around the world, threatening sustainable rice production. While conventional rice farming practices consume large quantity of freshwater supply (Cantrell & Hettel, 2005; Gautam, 2008), aerobic rice cultivation is observed as a promising water saving practice with minimum yield reduction given the right rice genotypes, in which climate change has become an issue threatening the freshwater supply (Zayed et al., 2023). Aerobic rice farming has been practiced in Hungary since the 1990s, which has successfully increased the rice yields by using tolerant aerobic rice varieties in the field (Jancsó et al., 2017; Simon-Kiss, 1997). In addition, it was revealed that drip irrigation combined with organic fertilizer application helps in promoting soil respiration, improve soil fertility, irrigation water use efficiency and nitrogen utilization by crops, while maintaining rice yield (Chhogyel et al., 2015; Yan et al., 2022; Yang et al., 2018). The application of combined fertilizer and irrigation has also been found beneficial to supply crops with its required nutrients and reduce nutrient losses (Ahmad et al., 2016).

Hence, motivated by the above, this study aims to investigate the effect of combined organic and inorganic fertilizers (CF), and rice husk biochar (RHB) on the rice yield, growth, nutritional quality, nitrogen uptake (NU), nitrogen use efficiency (NUE), and water productivity (WP) under aerobic rice cultivation utilizing drip irrigation system. The study utilizes hand-held SPAD equipment, SpectraVue leaf spectrometer, and unmanned aerial vehicle (UAV)-based aerial imaging in the experiment to assess the effects of the fertilizer treatments on plant health, yield, growth, quality, and water productivity.

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2. LITERATURE REVIEW

2.1. Integrated nutrient management

According to FAO (2022), nutrient imbalance significantly prevents the path towards food security as it directly affects food production, quality, and safety. Hence, sustainable management of nutrients in food production is one of the key factors to achieve sustainable food security.

Integrated nutrient management (INM) is the optimum use of soil N, crop residues, manure, BNF, and mineral fertilizer, which increases crop NUE (Ladha et al., 2005). This usually involves the integrated use of manure and mineral fertilizer, to improve physical properties of soil, plant growth, and sufficient supply of macro- and micro-nutrients needs for the plants. It is related to the integrated soil fertility management (ISFM) approach, which emphasizes combining both organic and mineral fertilizers to improve crop yield (Pincus et al., 2016). Research has found that continuous application of chemical fertilizers will cause crop yield reduction, declining soil health, leading to nutrient imbalance, and caused environmental problems by affecting freshwater supply through surface runoff (Kumar et al., 2022). However, the integrated use of organic fertilizer with chemical fertilizers were shown to sustain crop productivity and improve fertilizer use efficiency (Bhandari et al., 2002; Kumar et al., 2022; Ladha et al., 2005; Pincus et al., 2016). To achieve optimum crop productivity, the 4R nutrient stewardship framework serves as a helpful tool for the purpose. The 4Rs refers to fertilizer use Best Management Practices (BMP), where it implies the application of the right nutrient source at the right rate, right time, and right place (Bruulsema et al., 2008; Fixen, 2009). It is integrated with the agronomic BMPs to achieve crop management objectives (Bruulsema et al., 2008).

Nitrogen (N) is required by plants for growth, and it is the most often limiting nutrients in crop production (Ladha et al., 2005). The integrated crop management includes Site Specific Nitrogen Management (SSNM) which aimed to improve the recovery efficiency of fertilizer application. When deciding the amount of fertilizer to be applied, SSNM knowledge on crop nutrient requirements and expected indigenous nutrient supply can be used for prescriptive and/or corrective application of N. The decisions made on the amount and timing of N application in the prescriptive N management are determined before seeding based on the N supply from expected crop N demand, N supply from indigenous sources, expected fertilizer N efficiency, and expected weather and pests' risk (Ladha et al., 2005).

2.2. Inorganic and organic fertilizers

Fertilizers are used to support sustainable agricultural production. The global demand for fertilizers increases with the growing population. There are three different types of fertilizers that are commonly used by farmers in agricultural production. These are organic fertilizers, bio-fertilizers, and inorganic fertilizers. While organic fertilizers are derived from living organisms in the form of manure, compost, crop residues, and municipal waste; bio-fertilizers, on the other hand are a term used for living or dormant microorganisms, such as bacteria, fungi, actinomycetes and algae (Dineshkumar et al., 2018; FAO, 2019). Meanwhile, inorganic fertilizers are derived from non-living organisms, which are in the form of chemical, mineral, or organic-synthetic.

According to FAO (2019), organic fertilizer is defined as 'carbon-rich fertilizer derived from organic materials, including treated or untreated livestock manures, compost, vermicompost, sewage sludge and other organic materials or mixed materials used to supply nutrients. Many studies have reported the use organic fertilizers such as cattle manure, cow urine, rice husk, crop residues, vermicompost, and wood vinegar, which have been shown to improve soil fertility, increase rice yield, and improve water use efficiency (Ebaid & El-Refaee, 2007; Gupta et al., 2019; Haefele et al., 2011; Orge & McHenry, 2013; Polthanee et al., 2015; Rahaman & Sinha, 2013; Salem, 2006; Widyaswari et al., 2017). Several research have shown that these fertilizers could help to improve soil structure and physical characteristics, soil fertility, increase organic matter – a key factor to restore and maintain soil health, and increase nutrient efficiency (Setiawati et al., 2020; Singh et al., 2019; Yassi et al., 2020). Organic fertilizer in the form of nitrogen (N) added to the soil has to go through the mineralization process to convert the organic N to inorganic mineral forms (i.e. NH_4^+ and NO_3^-), to be utilized by the plant (Ladha et al., 2005).

Inorganic fertilizer, on the other hand, is defined as 'a nutrient-rich fertilizer produced industrially by chemical processes, mineral extraction or by mechanical grinding' (FAO, 2019). These fertilizers can be found as single or compound fertilizers. Single fertilizers are those that contain only one nutrient of nitrogen (N), phosphorous (P), potassium (K), sulphur (S) or other nutrients. Some examples of single fertilizers are urea, triple superphosphate, and potassium chloride. On the other hand, compound or mixed fertilizers are usually referred to as NPK fertilizers, which contain 2 or 3 macronutrients. Several examples of these fertilizers are diammonium phosphate and Triple 15 (N, P, K). Due to ease of application, these fertilizers are widely used by the farmers to increase their crop production. The use of synthetic nitrogen (N) fertilizer was reported contributing to 30-50% of crop yield, which significantly improved crop production (Song et al., 2022). However, the high fertilizer price has affected crop production especially in the low-income country (Bonilla Cedrez et al., 2021; Falconnier et al., 2023). Nitrogen fertilizers particularly have cost the agriculture industry billions per year (Ladha et al., 2005). Besides that, the irrational use of these chemical fertilizers can cause environmental and health problems, where nutrient runoff from the fertilizer pollutes waterways and can lead to eutrophication. The phosphate mining activity in the production of chemical fertilizer is also environment destructive.

2.3. Rice husk biochar (RHB) as plant nutrient sources

The use of biochar in agriculture has gained an increasing interest over the past decades to increase crop productivity with increasing in world population and the emergence of global issues such as climate change, environmental contamination, and soil erosion (Creamer & Gao, 2016; Nair et al., 2017; Zanli et al., 2022). The utilization of biochar in the field is also seen as a strategy to reduce agricultural waste and promote sustainable agricultural practices through re-utilization of the crop residues (Singh Karam et al., 2022). Rice is one of the main cereal crop productions in the world where most people consume rice in their daily diet. Major by-product from rice production is rice straw, rice bran and rice husk (Singh Karam et al., 2022). Globally, about 800-1000 million tons of rice straw is produced (IRRI, 2020), with 120 tonnes of rice husk and 76 million tonnes of rice bran are produced annually (Bodie et al., 2019; Kahlon, 2009).

Biochar is described by the International Biochar Initiative (IBI) as ‘a solid material obtained from the carbonization of biomass’, which happened when biomass such as crop residues, wood or manure is heated in a closed container with little or no air (Lehmann & Joseph, 2015). The heating process, known as pyrolysis, was carried out at certain temperatures, with varying degrees of temperature was reported to have effect on the quality of biochar produced (Nair et al., 2017). However, the temperature of which biochar was produced may not affect the phosphorous (P) release properties from the biochar applied to the soil (Nair et al., 2016), suggesting biochar produced using simple technique was like a complicated one and give similar benefits on a given soil.

The benefits of biochar on soil properties have been widely recognized. A meta-analysis study on biochar has found that the soil pH, N, P, K, and total C increased in the biochar amended soil compared to the soil without biochar application (Biederman & Harpole, 2012). It was also reported that biochar amendment has significantly improved the soil physical properties (Omondi et al., 2016). Biochar was shown to enhance soil organic matter (SOM) available in the soil by increasing carbon (C) storage in the soil (Nair et al., 2017). It also helps to decrease soil bulk density (BD) and increase soil water-holding capacity (WHC) due to the high surface area, porosity, and surface charge of biochar (Laghari et al., 2016; Nair et al., 2017; Omondi et al., 2016; Pratiwi et al., 2016; Zanli et al., 2022). The sorption characteristics of biochar to adsorb nutrients in the soil is influenced by both biochar characteristics and soil properties (Pratiwi et al., 2016), which is the reason for its increasing use in soil remediation and environmental management (Ippolito et al., 2012). Besides that, biochar also helps in soil amendment by increasing beneficial microbial biomass, N mineralization rates, enhanced P availability, available K concentration, soil respiration, and decrease plant and soil-borne diseases (Figure 1) (Asadi et al., 2021; Nair et al., 2017; Schneider & Haderlein, 2016), thus providing a desirable environment for plant growth and production. It was reported that biochar derived from manure or crop residue will tend to promote microbial growth more than wood-derived biochar (Gul et al., 2015). In addition, biochar was also applied to the soil to mitigate climate change and effect on greenhouse gas emissions by increasing soil C sequestration in the soil (Asadi et al., 2021; Nair et al., 2017). It was found that biochar 'can hold carbon in soils for hundreds to thousands of years' (Lehmann et al., 2006).

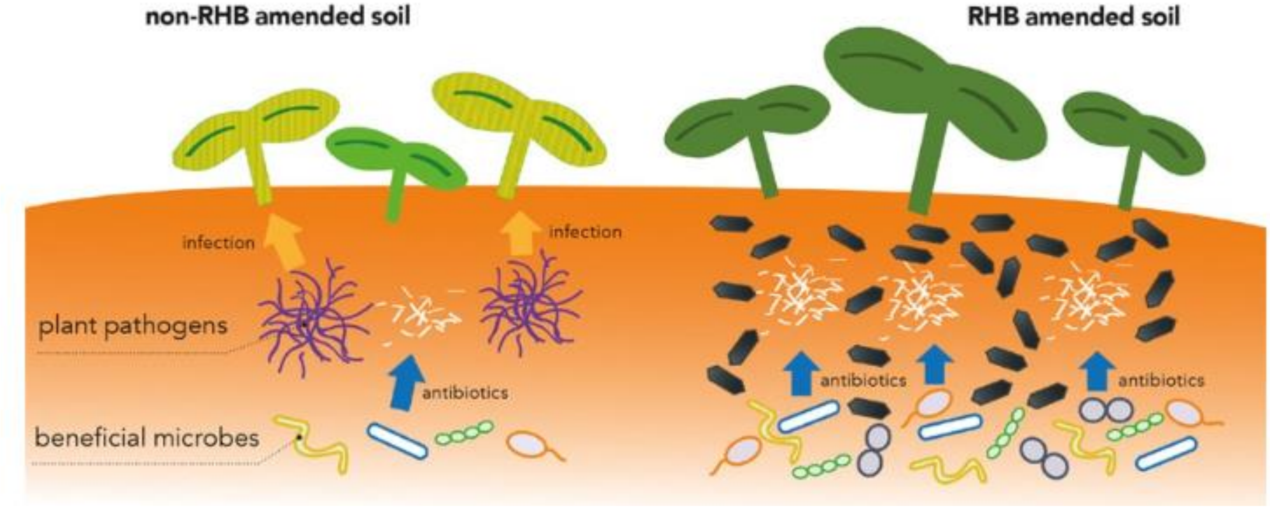

Figure 1: Schematic diagram of plant pathogens' protection mechanism in RHB amended soil (extracted from Ebe & Ano, 2020).

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Several common feedstocks used in biochar include forestry by-products, manures, agriculture residues, and organic industrial waste (Singh Karam et al., 2022). Freitas et al. (2016) suggested that some nutrient contents such as potassium (K) in biochar made from the animal feedstock would not necessarily be higher than those of the plant-based biochar. Therefore, plant-based biochar is as effective as animal-based biochar. In addition, the availability of agricultural crop residues in a region, such as rice, maize, sorghum, millets, sugarcane bagasse, banana stripes, and oil palm fronds, are important as it may be used as biochar (Zanli et al., 2022). In a study to investigate the effect of wood biochar on rice growth and yield, the results of the study have revealed the significant effects of biochar on rice yield and its components, including number of tillers, number of grains per panicle, panicle density, percentage of filled grain, and thousands-grain weight (Lakitan et al., 2018). Rice husk biochar (RHB) combined with fertilizer was found to improve soil fertility and crop yield by enhancing nutrient retention and water retention due to the high silica content of RHB, which resulted in decreased reliance of chemical fertilizers (Kimetu et al., 2008; Singh Karam et al., 2022; Yeboah et al., 2009; Zanli et al., 2022). On the other hand, a study applying biochar and inorganic N fertilizer together has shown enhanced rain-fed rice yield and yield components, and soil nutrient availability by minimizing nitrate leaching (Oladele et al., 2019). In another study, integrated nutrient management using combined inorganic fertilizers with farmyard manure and biochar was found to increase maize yields and improve levels of SOC, N, P, and base cations without any significant impact on soil pH and salinity (Arif et al., 2016). A comprehensive review on the effect of biochar amendment on soil quality and rice productivity has revealed a positive effect of biochar on soil quality, and rice yield under N fertilizer application, with a close relationship between the effect of biochar amendment on rice yield and N use efficiency (Huang et al., 2013). Likewise, biochar amendment was also found to increase soil nutrient content, affect N transformation process, and modify soil microbial properties, considering the biochar type and quantity factors (Li et al., 2016).

2.4. Nutrient for rice affected by climate change

Plants depend on soil and water for their growth, and it serves as a foundation for agricultural production (Hatfield et al., 2020). Soil provides mechanical and nutrient support necessary for plant growth, while water is essential for plant life processes. According to FAO (2022), about 95% of the food nutrients come from soils, which naturally supports the crop growth. It contains different amounts of macro- and micronutrients in the form of mineral, organic matter and living forms.

Plants require several of these essential nutrients from the soil for growth and production. Macronutrients (i.e. nitrogen (N), phosphorous (P), and potassium (K)) are the nutrients required in large amounts by plants. While micronutrients are those that are required in lesser quantities, such as iron (Fe), manganese (Mn), and zinc (Zn) (FAO, 2022). Of the 18 essential elements which plants require for growth, 15 of these elements are provided by the soil (FAO, 2022). A deficiency of an essential nutrient will make it impossible for the plant to complete the vegetative or reproductive stage of life cycle (Arnon & Stout, 1939; Roy et al., 2006).

Healthy soil contributes to nutritious foods and is determined by the fertility of a soil. FAO (2019) defines soil fertility as ‘the ability of a soil to sustain plant growth by providing essential plant nutrients and favorable chemical, physical and biological characteristics as a habitat for plant growth’. While different soils contain different amounts of nutrients, and to assess the nutrient supply to crops, it is necessary to know the amount of available soil nutrients (Roy et al., 2006). For this, it is recommended to carry out annual soil sampling and testing to determine the nutrient status of the soil in the field and to make nutrient management decisions. It was reported that nitrogen (N) is the most often limiting nutrient in crop production (Ladha et al., 2005), and there is a close relationship between the amount of N applied to the soil and grain N content, which determines crop yield (Wilson et al., 2001; Swain & Sandip, 2010). This nutrient can be added to the soil through mineralization of soil N, biological nitrogen fixation (BNF), fertilization, atmospheric deposition, irrigation, rainwater, and residues (FAO, 2022; Ladha et al., 2005). A study has found that 1 kg of N is required to produce 68 kg of rice (Witt et al., 1999). Considering this, it is therefore important to provide plant nutrients at adequate level, in the bioavailable forms that can be absorbed by the plants (FAO, 2022). Nutrients present in organic and mineral forms must be solubilized from mineral sources and mineralized from organic sources (including soil organic matter) to be usable by plant roots (Roy et al., 2006). For example, plants can only take up N in the form of nitrates (NO_3^-) and ammonium (NH_4^+) through mass flow process. While phosphorous (P) and potassium (K) can only be taken up by plants through diffusion from soil to the roots (FAO, 2022; Hodges, 2010).

Temperature is one of the factors affecting nutrient mobilization. A higher temperature will result in increasing humus decomposition and nutrient mobilization in the soil (Roy et al., 2006). Microbial activity will also be likely to occur more at warmer and increased temperature as microbes break down soil organic matter at faster rates compared to cooler temperatures (Pilbeam, 2015). As a result, N minerals released into the soil will be increased with the enhanced rate of nitrification from the increased in warming effect. However, it was revealed that there is no certainty that an increase in N mineralization rate with increased in temperature will result in long-term effect because of the soil microbial respiration process which occurred over long period of exposure and may decreased N mineralization rate (Bradford et al., 2008; Dieleman et al., 2012; Pilbeam, 2015). Concerning this and in relation to the global climate change, studies have shown that increasing climate variability, including increasing in atmospheric carbon dioxide (CO_2) concentration and global temperatures are expected to have direct effect on crop growth and physiological processes, which then affected the crop productivity, grain quality and crop nutrient content (Beach et al., 2019; Wang et al., 2020). It was revealed that increasing atmospheric CO_2 from the greenhouse gases emissions are projected to alter the nutritional quality of crops, especially on main cereal crops such as wheat, rice, barley, oats, and potatoes (Ebi et al., 2021), and not all rice cultivars were currently adapted to the current CO_2 concentration (Ziska et al., 2012). In addition, soil erosion affected by climate change due to increase in rainfall amount and intensity through water erosion could result in decreased on soil productivity and fertility and increased in loss of soil organic carbon and nutrients, affecting N mineralization by microbes and availability in the soil which was important in plant growth and production (Hatfield et al., 2020; Lori et al., 2020).

2.5. Aerobic rice cultivation, potential and constraints

Rice is the major consumer of irrigated water. It can be grown in puddled and non-puddled environment conditions. The rice thrives in aerobic environments where the actual water need is found lesser than the water requirements (Ouoba et al., 2022). The rice varieties used in a specific area determine the adaptability of the irrigated crop. Aerobic rice farming is seen as one of the most promising, eco-friendly technologies in consideration of water saving under the effect of climate change (Rajakumar et al., 2009). It is a farming practice developed by the International Rice Research Institute (IRRI) to address the water scarcity in tropical agriculture (Priyanka et al., 2012). The system increases water productivity by reducing water use and limiting seepage, percolation, and evaporation (Nie et al., 2012). Rice can be dry direct-seeded or transplanted where soils are kept in aerobic, well-drained and un-puddled conditions (Nie et al., 2012; Rajakumar et al., 2009; Zhao et al., 2010). It is developed for lowland and upland areas where water supply is an issue, and with access to supplementary irrigation (Belder et al., 2005). Various improved rice cultivars were used in aerobic rice farming depending on the adaptation of the rice species to the climate conditions in the area. In Malaysia, for example, aerobic rice cultivars with the combination of both upland and lowland rice varieties characteristics, is grown aerobically in the upland environments (Chan et al., 2012; Tuong & Bouman, 2003). Given light and frequent sprinkler irrigation, the rice cultivated under aerobic conditions was found to improve water productivity from 0.4 to 0.6 kg/m^3 compared to flooded rice farming, with decreased in rice yield (Chan et al., 2012). Similarly, irrigation water use was found lower by 41% in the aerobic rice system using Apo cultivar in the Philippines compared to the flooded conditions, but with decreased in rice yield (Belder et al., 2005). On the other hand, rice yield was reported higher in the Japan with a temperate climate compared to the tropics, which was mainly due to the use of high-yielding rice varieties and increasing nitrogen uptake during the reproductive stage which allows the crop to produce more spikelets and biomass (Kato & Katsura, 2014; Kato et al., 2009).

Drip irrigation is one of the best options in aerobic rice cultivation, by providing rice with sufficient moisture, close to the crop water requirement on a continuous basis. It was found that drip irrigation considering the lateral spacing was better to reduce irrigation water use and increasing water productivity and grain yield, while increasing economic return compared to flooding system (Parthasarathi et al., 2014; Parthasarathi et al., 2017; Samoy-Pascual et al., 2022). This lateral spacing helps to optimize the number of rows of rice plants per dripline, hence resulting in improving water productivity in relation to the conventional flooding (Samoy-Pascual et al., 2022). A comprehensive review of water productivity in aerobic rice showed that the use of drip irrigation helped to increase water productivity in aerobic rice, while reducing N fertilizer requirement compared to the flooded rice (Fukai & Mitchell, 2022). A study comparing surface drip (DI) and subsurface drip systems (SDI) in aerobic rice cultivation showed that DI has higher yield than SDI, and better water productivity compared to conventional flooding (Çolak, 2021).

Studies have reported the primary constraints of rice yield, including water deficit, infertile soils, weed competition, N application, continuous cropping, and pests and diseases (Kreye et al., 2009; Lafitte et al., 2002; Nie et al., 2012; Rajakumar et al., 2009). Recommendations were given including improving irrigation and nutrient management, crop management practices, crop rotation, soil acidification, breeding new aerobic rice cultivars, and selecting and developing

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suitable rice genotypes to increase the rice yield (Chauhan et al., 2011; Lafitte et al., 2002; Nie et al., 2012; Zayed et al., 2023). In the case of aerobic rice cultivation in Japan where rice yield is not a concern due to the effective N management and control of spikelet density, research on the development of suitable rice genotypes is still required, which covers the adaptive responses of rice root system in water uptake for more water use efficient and productive aerobic rice culture (Kato & Katsura, 2014). Selection strategies to identify suitable genotypes and traits for development of aerobic rice varieties that are high yielding and drought tolerant were also required in the tropics and other regions which were threatened by water issues (Fukai & Mitchell, 2022; Lafitte et al., 2002; Zaman et al., 2018; Zhao et al., 2010). In addition, increasing aerobic rice seeding rates could also help to increase rice yield by suppressing weed growth and reduce grain yield losses from competition of weeds (Chauhan et al., 2011). In Hungary where aerobic rice has been successfully developed with aerobic rice varieties breeding started in the 1990's, the yield and quality of rice were found to be largely affected by climate tolerant rice varieties, sowing practices, weed management, and irrigation requirement (Jancsó et al., 2017). Hence, integrated weed management is the most suitable approach to weed management to determine the success of aerobic rice cultivation (Jabran & Chauhan, 2015).

2.6. Indirect measurement of rice leaf nitrogen content and health

Several methods were used in non-destructive estimation of plant N content, including leaf color charts (LCC), chlorophyll meter, reflectance spectra, and chlorophyll fluorescence (Huang et al., 2008; Lin et al., 2010; Nguyen & Lee, 2006; Shukla et al., 2004; Wang et al., 2021b). The chlorophyll meter or also known as the SPAD meter is one of the widely used hand-held tools, to indicate leaf chlorophyll concentration, for corrective nitrogen management and to increase nitrogen use efficiency (NUE) in the rice field (Cabangon & Tuong, 2011; Ladha et al., 2005; Parry et al., 2014). It is one of the simple, quick, reliable, and non-destructive methods to estimate rice leaf nitrogen content and to identify crop demand for nitrogen (Cabangon & Tuong, 2011). Studies have shown a linear relationship between chlorophyll and plant leaves N content, and between leaf N content and SPAD values, indicating that chlorophyll contents can be used as an alternative to measure plant N status, and SPAD meter can be used to assess crop N status and plant need of N fertilization (Swain & Sandip, 2010).

Nitrogen (N) is the most important nutrient for plant growth, yield, and quality (Sarker et al., 2015). Excessive or under application of N fertilizer will determine the health of the plant and will be shown through the appearance of the plant's leaf, from greening to yellowing (Sarker et al., 2022). By utilizing these tools, crops N status can be estimated, and the number of fertilizers could be applied based on the crops' need as determined by the data obtained from the device. Generally, the fully extended topmost leaf of the growing plants is used to determine the need and timing for N top dressing in rice (Lin et al., 2010; Wada et al., 1986). This SPAD-based N management utilizes the benefits of the strong relationship between SPAD readings versus leaf N content and has been reported successfully increasing NUE while maintaining high rice yield (Cabangon & Tuong, 2011). Concerning sustainable rice production, chlorophyll meter-based N scheduling would be significant and effective in integrated nutrient management which involved organic manure application (Ghosh et al., 2023).

In addition, the leaf N content or chlorophyll of crops is an important indicator of plant health, photosynthetic efficiency, and crop productivity (Bussotti et al., 2020). The chlorophyll meter helps to determine the health of the plants, where varied N status in plants is affected by different environmental and stress factors. For example, chlorophyll meter allows users to measure leaf greenness or leaf chlorophyll content quickly and easily by giving SPAD (Soil Plant Analysis Development) values, where the values provided are correlated with the crop leaf N content, which is affected by various factors including fertilizer application, weather, stress caused by excess or limited water, and pests and diseases (Cabangon & Tuong, 2011). Plant growth is linearly dependent on N supply, and in a situation where N fertilizer application is not following to the crop demand, the result is that crop will have smaller leaf area (Fernandez et al., 1996), meaning lower leaf photosynthesis and chlorophyll content, leading to low NUE and biomass production (Lin et al., 2010; Singh et al., 2002; Sun et al., 2017; Zhao & Oosterhuis, 2000), and above the N range, can result in problems where it does not necessarily improve crop yield and could even cause water pollution, plant stress, overproduction of leaves, and more unproductive tillers (Carpenter et al., 1998; Sun et al., 2017; Wang et al., 2021b).

Additionally, like the SPAD meter, SpectraVue leaf spectrometer is a rapid, powerful, non-destructive hand-held measuring device, which measures plant stress. Using the built-in indices, it measures transmission, absorption, and reflection, as well as other plant stress and pigment

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indicators (CID Bio-Science, 2023). In recent research studying the effects of cold stress on rice seedlings in Szarvas, Hungary, SpectraVue was used to help monitor the spectral properties and chlorophyll-a in rice seedlings under natural cold stress (Székely et al., 2023). This passive spectrometer uses sunlight as the light source and has a wide spectral range with high spectral resolution (Sun et al. 2017). As leaf nitrogen concentration (LNC) is associated with the capacity of plant leaves to carry out photosynthesis activities, the spectrometer could help to acquire the reflectance indices covering the visible and red-edge region which serves as an important indicator of chlorophyll and N (Sun et al., 2017). The data acquired could then be used to guide in fertilization and to help in understanding carbon and N cycles (Sun et al., 2017).

2.7. UAV survey methods of rice chlorophyll and nitrogen content

The aerial observation of agricultural areas and crops dates back several decades. Initially, satellite aerial images were used, but today, drone aerial images take precedence. Satellite technology offers global coverage with lower spatial resolution, making it suitable for broad-scale observations on a fixed schedule. It involves higher initial costs and delayed data access. In contrast, UAV technology provides localized, high-resolution monitoring with on-demand flexibility at lower initial costs. UAVs offer real-time or near-real-time data acquisition, making them ideal for targeted and timely observations. The choice between the two depends on factors such as scale, resolution, temporal needs, and budget constraints. Combining satellite and UAV data can provide a comprehensive view of agricultural landscapes.

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are efficient and precise tools for crop management. These autonomous flying devices equipped with cameras and sensors offer farmers valuable insights into their fields, transforming traditional farming practices. UAV technology in agriculture enables remote sensing, data collection, and analysis at high levels of detail and accuracy. Remote sensing-based mapping of crop nitrogen (N) status has been widely applied to determine physiological conditions of plants in making precise nitrogen management (Sun et al., 2017; Wang et al., 2021b). It is associated with precision agriculture where this technique is often combined with artificial intelligence (AI) for guidance in agronomic management (Hatfield et al., 2008; Hatfield et al., 2019). For instance, UAV-based hyperspectral images were used in combination with the modern machine learning (ML) methods to estimate different paddy rice N traits (Wang et al., 2021b). It provides a cost-effective, time-saving, and non-destructive monitoring of crop N status covering over a large geographic area (Perros et al., 2021; Wang et al., 2021b). The application of this technology provides users with spatial information that is difficult to obtain on the ground (Hatfield et al., 2019). It is seen as a practical alternative method compared to the complicated, low, and expensive chemical methods or the traditional hand-held method, and is often used for validation purposes with the conventional methods (Huang et al., 2004; Sun et al., 2017). For example, in a cold stress study, hand-held spectrometer data were validated with the data acquired with the drones for the chlorophyll-a fluorescence measurements (Székely et al., 2023). On the other hand, UAV equipped with multi- or hyperspectral cameras were also used to acquire florescence spectral information for estimating rice yield (Wang et al., 2021a). Compared to the hand-held meters, the remote sensing method offers more information with many available wavelengths of the reflectance spectroscopy which also provide a basis for calculating other pigments' content (Hatfield et al., 2008).

Unmanned aerial vehicles (UAV) equipped with multispectral, thermal imaging and/or hyperspectral cameras can provide high spatial and temporal resolution remote sensing data on the rice canopy, which makes monitoring of the crop leaf nitrogen concentration and yield possible at different growth stages (Perros et al., 2021; Sun et al., 2017; Wang et al., 2021a; Wang et al., 2021b). The reflectance values calculated from the built-in indices in the processing software provide different combinations of wavebands which give an estimation of crop biophysical features, such as biomass, leaf area or yield (Hatfield et al., 2019). For example, the chlorophyll indices are related to the leaf chlorophyll content which gives an indirect estimation of the crop nutrient status, and the plant biophysical indices, such as Normalized Difference Vegetation Index (NDVI), Green NDVI (GNDVI) and Red Edge NDVI are related to vegetation cover and leaf area (Hatfield et al., 2008; Hatfield et al., 2019; Perros et al., 2021).

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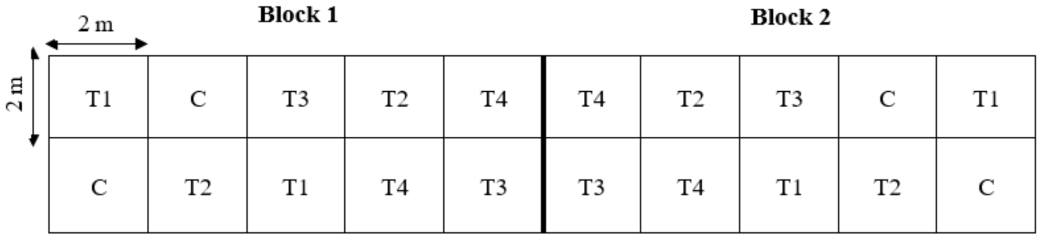
3. MATERIALS AND METHODS

3.1. Experimental Area and Design

The research was conducted from the end of April to September 2023 at the Lysimeter Station of the Hungarian University of Agriculture and Life Sciences, Institute of Environmental Sciences, Research Centre of Irrigation and Water Management (MATE IES ÖVKI) in Szarvas, Hungary. The field experiment was carried out in a randomized complete block design (RCBD) in five treatments (including control) and two replications in two blocks, with a total of 20 plots. Each plot was planted with two to three seedlings in a 2 m x 2 m square plot with 2-3 cm plant spacing, and 25 cm between rows. Weed management was carried out every three weeks after sowing, and additional weeding every 10 days until shading of soil from plants. Drip irrigation was applied at the initial rate of 1 L/m^2 per day, and it was modified according to the weather condition. An aerobic rice variety known as ‘M 488’ was sown using a portable drum seeder.

The treatments were marked C (controls), and T1 through T4, as followed: C = No fertilizer application; T1 = 100 kg N/ha NPK 15:15:15; T2 = 100 kg N/ha NPK 15:15:15 and 1 t/ha RHB; T3 = 50 kg N/ha NPK 15:15:15 and 3 L/m^2 organic fertilizer; and T4 = 50 kg N/ha NPK 15:15:15 and 3 L/m^2 organic fertilizer and 1 t/ha RHB. Summary of the experimental layout and design was outlined in Figure 2 and Table 1 below.



Block 1					Block 2				
T1	C	T3	T2	T4	T4	T2	T3	C	T1
C	T2	T1	T4	T3	T3	T4	T1	T2	C

Figure 2: Experimental layout.

Table 1: Summary of the experimental design.

Treatments	**Inorganic fertilizer (kg N/ha)**	**Organic fertilizer (L/m^2)**	**RHB (t/ha)**
C	0	0	0
T1	100	0	0
T2	100	0	1
T3	50	3	0
T4	50	3	1

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3.2. Weather data collection

Weather data during the growing period in the experiment were collected from an automated weather station (Agromet-Solar, Boreas Ltd., Hungary) on a daily and monthly basis. Average monthly maximum, minimum and mean temperature, and precipitation were recorded.

3.3. Soil sampling and analysis

Initial and final soil samples were collected from the experimental area using an auger, spatula, and plastic bucket. Four plots at two ends of each block were sampled from the experimental field, with each plot randomly taken four sub-samples at 30 cm soil depth. The soil samples were sent to the MATE ÖVKI Laboratory for Environmental Analytics. The initial surface soil properties taken at soil depth (0-30 cm) prior to the start of the study were shown in Table 2.

Table 2: Average initial soil properties at the experimental site of two treatment blocks taken in 0-30 cm soil layer in 2023.

Parameters	**Treatment blocks**	
	1	**2**
pH (KCl)	7.36	7.31
Soil plasticity index (according to Arany)	35.5	37.5
Water soluble salt (m/m%)	<0.02	0.03
Carbonated lime (m/m%)	2.07	1.57
Humus	1.89	2.16
NO_2^--NO_3^--N (mg/kg)	6.38	9.74
Total P (mg/kg)	1355	1935
K_2O (mg/kg)	406.5	481
Na (mg/kg)	108.6	100
Cu (mg/kg)	3.2	4.7
Mn (mg/kg)	66.3	100.4
Zn (mg/kg)	2.7	3.5
Sulfate content (mg/kg)	21.8	18.2
Mg (mg/kg)	163.5	187.5

3.4. Fertilizer preparation and analysis

The organic fertilizer solution was prepared two weeks before the experiment. The fertilizer solution was prepared in 100 L plastic barrel, which composed of 90 L freshwater, 8 L of fresh pig manure, 1 kg of soybean pellet, 0.5 kg of brown sugar, and one handful of healthy soil. All the ingredients were mixed into the plastic barrel and were kept in the shade. The fertilizer solution was stirred thoroughly twice per day for one week to mix all the ingredients. The solution was

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ready to use after a week. It was applied at sowing and early seedling growth stages. The solution samples were sent in two repetitions to the MATE ÖVKI Laboratory for Environmental Analytics.

Inorganic fertilizer in the form of ammonium sulphate ($(NH_4)_2SO_4$), super phosphate (P_2O_5) and muriate of potash (K_2O) at the ratio of 15:15:15 were used in the experiment. The amount of NPK nutrients in both the organic and inorganic fertilizers applied to the soil was determined based on the maximum allowable nitrogen application for agriculture crops in the country at 100 kg N/ha.

3.5. Preparation of rice husk biochar (RHB)

In the preparation of RHB, rice hull was carbonized according to the principle taken from Orge & McHenry (2013). The rice hull used in the experiment was from 'M 488' rice variety. The carbonization process was carried out at the NAIK ÖVKI (National Agricultural Research and Innovation Centre, Research Institute of Irrigation and Water Management, Szarvas, Hungary) during the spring period of 2019. A central chimney and fireplace were prepared using commercially available steel mesh (5x5 mm). For the start of carbonization, firewood was placed. A small pile of rice hull was built around the central chimney and ignited in the chimney. After a few hours, the pile of rice hull was transformed into biochar. At the end of the process, the hot biochar was poured with some water to prevent ash formulation.

The nutrient composition of the rice hull before and after carbonization were analysed in two repetitions. The analysis was made at the accredited NAIK ÖVKI Laboratory for Environmental Analytics (Szarvas, Hungary) using the standardized Hungarian methods (MSZ).

3.6. Plant nitrogen status and chlorophyll content

The nitrogen status of crop was regularly monitored up to the ripening stage by analyzing the chlorophyll content (SPAD value) of rice flag leaf using hand-held Minolta chlorophyll meter, SPAD-502, Japan. A fully matured top leaf of the plant was selected for SPAD value recording with an average of ten readings taken in a plot.

SpectraVue leaf spectrometer CI-710S was used to measure reflection, transmission, and absorption values for plant health and growth determination. Measurement was taken by selecting a fully matured top leaf of the plant and an average of ten readings were taken per plot. The data acquired was used to study its relationship with rice yield.

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3.7. UAV-based multispectral and thermal image acquisition

Aerial images were taken using a DJI Matrice 300 quadcopter UAV equipped with a multispectral camera (MicaSense RedEdge-MX; bands: red, green, blue; red-edge, and near-infrared), and DJI H20t thermal camera. Thermal images collected for the purpose of examining heat stress on plants during several critically dry days. The images were acquired at an altitude of 30 m during the booting, heading, flowering, and ripening of the spikelets. The UAV flight was taken under clear sky at low wind speed weather conditions. Upon image processing, different vegetation index maps, including NDVI, GNDVI, BNDVI and NDRE were generated in Pix4D Fields software (Figure 3). The vegetation indices were calculated according to the following formula:

$$NDVI = NIR - RED/NIR + RED$$

where, NDVI (Normalized Difference Vegetation Index) measured the difference between near-infrared (NIR) and red (R) light. Healthy vegetation reflected more NIR and absorbed more R light.

$$GNDVI = NIR - Green/NIR + Green$$

where, similar to NDVI, GNDVI (Green Normalized Difference Vegetation Index), used green (G) instead of red (R) light.

$$BNDVI = NIR - Blue/NIR + Blue$$

where, BNDVI (Blue Normalized Difference Vegetation Index) used blue (B) light instead of red or green. The index was used to distinguish between water and vegetation.

$$NDRE = NIR - Red\ Edge/NIR + Red\ Edge$$

where, similar to NDVI, NDRE (Normalized Difference Red Edge Index) used red edge (RE) band instead of the red band. The index was used to assess vegetation health.

Specifically, for the statistical analyses, digital point sampling was conducted on the index maps. Then, ten digital samples were taken in each experimental plot (Figure 3). After that, vegetation indices obtained were compared with the vegetation indices calculated from hand-held chlorophyll meter data and leaf spectrometer data, to determine the relationship between different indices to best represent the rice leaf nitrogen content under experimental conditions.

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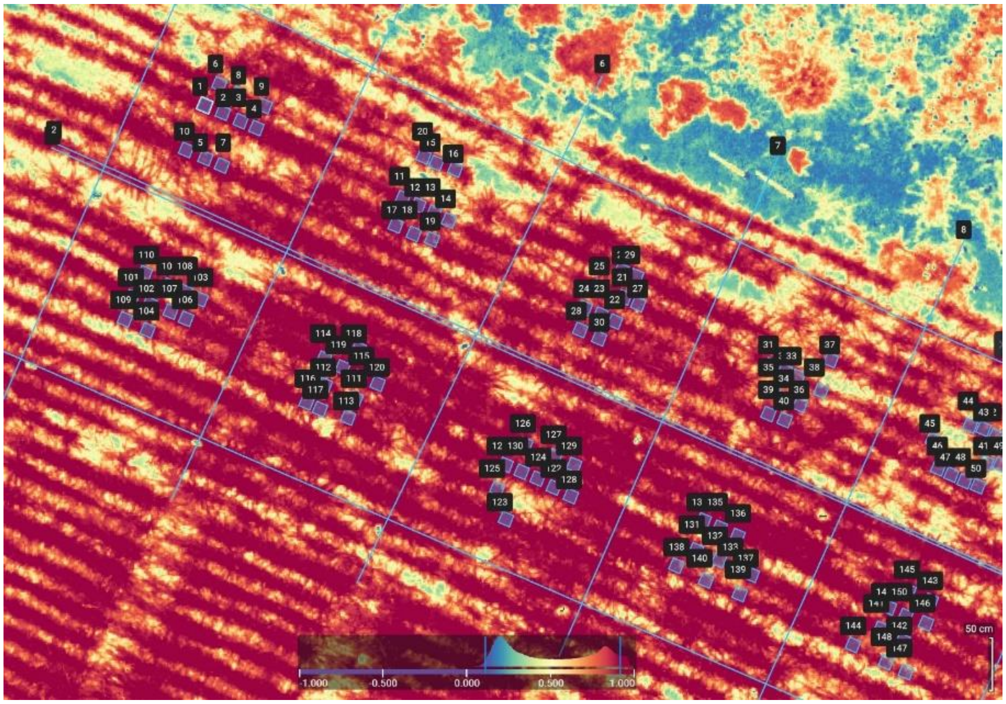

Figure 3: Digital sampling of the NDVI map in Pix4D Fields software.

3.8. Measurement and calculations

3.8.1. Rice growth

Paddy plant height was measured from the stem base of a plant to the tip of the longest panicle for each treatment. Plants near the border hills of the plots were excluded from the measurement.

3.8.2. Rice yield (RY)

The rice sheaves were stored in a greenhouse and left to dry for about two weeks until the rice grain moisture was constant. The rice moisture content was measured using moisture analyzer KERN MLS50-3 at 120°C. Five representative samples were taken for the analysis of the moisture content. Rice yield per unit area was calculated according to the following formula:

$$Rice\ dry\ weight\ (\%) = \frac{final\ weight}{initial\ weight} \times 100\%$$

$$Rice\ yield\ per\ plot = \frac{(weight\ of\ one\ bag\ \times rice\ dry\ weight\ \%)}{100}$$

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3.8.3. Rice biomass

Rice sheaves harvested from each plot were stored in a greenhouse and left dry for about two weeks until the shoots, leaves and panicles achieved constant dry weight. The biomass of the rice sheave was determined by dividing dry weight with the area for one plot of the rice plants. The sheaves were removed from its shoots and leaves, leaving only panicles, and were placed in a threshing machine. The rice grains collected were weighed. Rice biomass was determined by dividing the dry weight of rice grains with the area for one plot of the rice plants.

3.8.4. Measurement of TGW

A sample of 1000 seeds were weighed for each treatment to measure paddy seeds thousand-grain weight (TGW). The husks were removed with Satake THU Laboratory Husker equipment. The cargo rice was weighed on analytical balance (PCE-BS 3000). The average TGW of paddy (TGWp) and cargo (TGWc) rice were calculated.

3.8.5. Measurement of HRP and BGP

Husk layer of 100g of seeds from each sample were removed and weighed. The brown grains were polished with Satake TM05 Test Mill laboratory equipment and were weighed. The whole polished rice (white grain) was separated and weighed. The broken grains were separated from the whole grains using a grain grader equipment. The whole grains collected were weighed. Head rice percentage (HRP) and broken grain percentage (BGP) was calculated using the following formula:

$$HRP\ (\%) = \frac{weight\ of\ whole\ grains}{weight\ of\ paddy\ samples} \times 100\%$$

$$BGP\ (\%) = \frac{weight\ of\ broken\ grains}{weight\ of\ paddy\ samples} \times 100\%$$

3.8.6. Measurement of Grain Dimensions (GD)

A few seeds from every sample were taken and scanned using a flatbed scanner (HP ScanJet Pro 3500 f1). The images were saved in Readiris Pro 14.1 software “tiff” format, for measurement of grain size and shape. The scanned pictures were transferred to “jpg” format and were analyzed using SmartGrain 1.2 software. Mean length (mm), width (mm) and L/W ratio were calculated.

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3.8.7. Water Productivity (WP)

Water productivity (WP) during the rice growing period was calculated using the following equation (Cabangon & Tuong, 2011; Çolak, 2021).

$$WP_{P+I} = \frac{Y}{(P+I)}$$

Where, WP = irrigation water amount (kg/m^3); Y = grain yield (kg/ha); and I = the amount of irrigation water (m^3/ha); P = total precipitation during the growing season (m^3/ha).

3.9. Statistical analysis

Analysis of variance (ANOVA) was used to investigate the effect of fertilizer and treatment blocks on rice growth, yield, quality, WP, NUE and rice NU. Differences between means ($p < 0.05$) were compared using Tukey's test. Weather data was summarized and presented in Walter-Lieth diagram using 'climatol' package. Correlation matrix, principal component analysis (PCA) and regression were computed in R software using packages including 'factoextra', 'FactoMineR', 'ggplot2', 'dplyr', 'gridExtra', 'psych', and 'tidyverse'. Pearson and Spearman tests were used to determine significant differences ($p < 0.05$ and $p < 0.01$) between each variable. All the data were analyzed using R software (version 4.3.2).

4. RESULTS

4.1. Weather data of the experimental area during the growing period

Figure 4 showed the average monthly temperature (°C) and total monthly precipitation (mm) at the experimental area in the lysimeter station in the year 2023. Overall, the highest temperature was found in the months of July and August with average temperatures of 24.2°C and 23.8°C respectively. The lowest temperature was recorded in the beginning (February) and end of the year (December), each with an average temperature of 3.0°C. On the other hand, the highest precipitation was recorded in November and December with total precipitation of 85.2 and 78.1 mm respectively. During the rice growing period from April-September, it received the highest rainfall in May, with total precipitation of 56 mm. The lowest precipitation was recorded in February, April, June, and October, with total precipitation of 15.1, 19.3, 20.1 and 21.3 mm respectively.

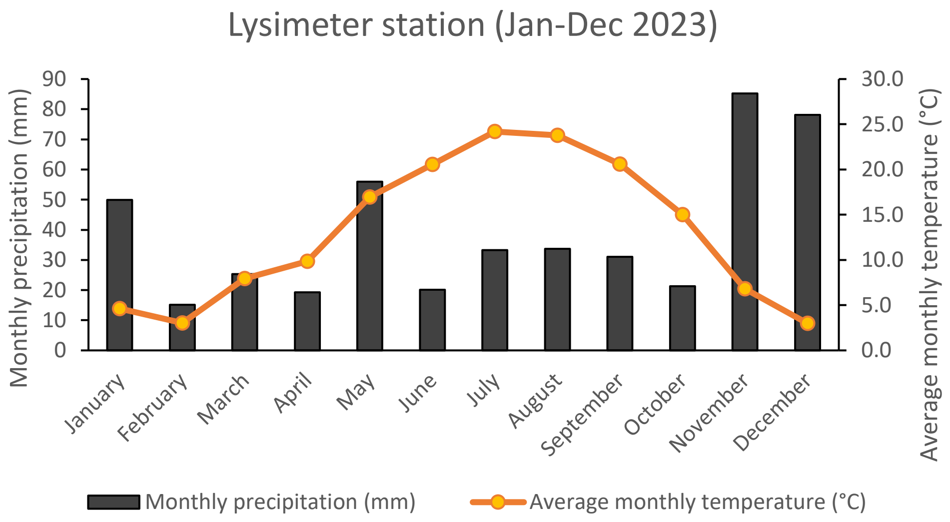

Figure 4: Average monthly temperature (°C) and monthly precipitation (mm) at the experimental field in the lysimeter station from January till December 2023.

Figure 5 summarized the monthly average weather conditions at the experimental area in the Lysimeter station during the growing period in the year 2023. The average annual temperature and precipitation was recorded at 13.2 °C and 15 mm respectively. The graph showed the temperature red line was above the blue line and was filled with dotted red vertical lines, indicating dry conditions and arid period throughout the growing period of 2023. The months where frost is likely to occur are from January to April, and October to December 2023.

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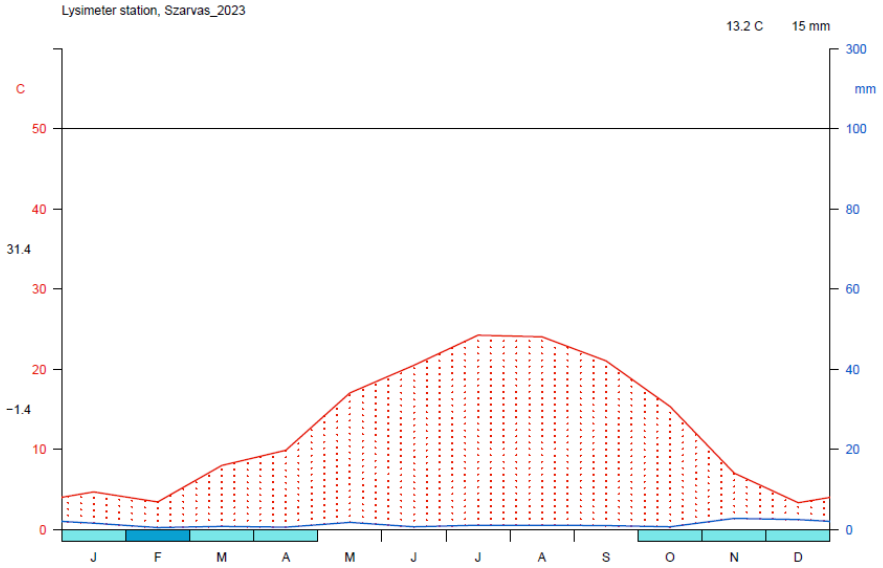

Figure 5: Walter-Lieth diagram of the experimental area in the growing period of year 2023.

4.2. Physical and chemical properties of soil samples

The final surface soil properties of each fertilizer treatment under two treatment blocks, taken at soil depth 0-30 cm after rice harvesting were shown in Table 3.

Table 3: Average final soil properties of each fertilizer treatment under two treatment blocks after rice harvesting.

Parameters	**Treatment blocks**	**C**	**T1**	**T2**	**T3**	**T4**
pH (KCl)	1	7.35	7.33	7.36	7.34	7.35
Soil plasticity index (according to Arany)		38.1	38.4	38.8	38.2	37.2
Water soluble salt (m/m%)		0.05	0.08	0.06	<0.02	0.04
Carbonated lime (m/m%)		1.57	0.99	1.45	1.41	1.43
Humus		1.96	1.94	2.06	2.08	2.08
NO_2^--NO_3^--N (mg/kg)		5.61	37.2	18.86	5.07	8.69
Total P (mg/kg)		2105	2115	2005	1915	1910
K_2O (mg/kg)		475	490	495	447	443.5
Na (mg/kg)		94.95	99.6	92.85	96.45	92.9
Cu (mg/kg)		4.17	4.13	4.26	3.79	3.8
Mn (mg/kg)		89.4	86.3	78.4	68.5	69.6
Zn (mg/kg)		2.7	2.7	2.6	2.5	2.4
Sulfate content (mg/kg)		14.9	19.7	16.6	16.2	14.4
Mg (mg/kg)		201.5	205	188.5	200.5	193

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pH (KCl)	2	7.26	7.28	7.29	7.27	7.29
Soil plasticity index (according to Arany)		39.1	40.2	40.5	39.9	38
Water soluble salt (m/m%)		0.04	0.08	0.08	0.06	0.05
Carbonated lime (m/m%)		0.63	0.84	0.88	1.22	1.06
Humus		2.1	2.16	2.18	2.1	2.09
NO_2^--NO_3^--N (mg/kg)		6.89	26.6	22.15	14.36	10.2
Total P (mg/kg)		2445	2365	2345	2255	2285
K_2O (mg/kg)		479	482	475.5	465	470
Na (mg/kg)		101.95	103	105.5	96.35	101.5
Cu (mg/kg)		6.4	6.3	6.3	5.8	5.3
Mn (mg/kg)		246.5	210	205	155.7	133
Zn (mg/kg)		3.8	3.6	4	3.3	3.1
Sulfate content (mg/kg)		15.2	17.95	19.25	15.45	14.8
Mg (mg/kg)		194.5	198	197.5	203.5	204

4.3. Inorganic and organic fertilizer nutrient composition

The inorganic fertilizer used in the study was complex fertilizer with nutrient composition of 15% nitrogen (N), 15% phosphate (P_2O_5), 15% potassium oxide (K_2O), 7% sulfate content (SO_3), and 0.01% zinc (Zn). While the nutrient composition of organic fertilizer following the laboratory analysis has the nutrient composition as followed: 790 mg/L (Total N), 196 mg/L (Total P), 3.9 (pH), 17600 mg/L (total dry matter content), 124 mg/L (NH_4-N), 159 mg/L (NH_4^+), 0.191 mg/L (NO_2-N), 0.629 mg/L (NO_2^-), < 0.1 mg/L (NO_3-N), and < 0.443 mg/L (NO_3^-).

4.4. Rice husk biochar (RHB) nutrient composition

Table 4 showed the nutrient composition of rice hulls before and after the carbonization process. Based on the analysis, average potassium (K) and calcium (Ca) content showed higher nutrient value (16055 mg/kg and 4680 mg/kg respectively) compared to phosphorus (P), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and arsenic (As).

Table 4: Nutrient composition of rice hull and rice husk biochar (RHB).

	P	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Cu**	**Zn**	**As**
Hull I.	702	6660	1300	589	60.0	131	<2.5	12.3	133
Hull II.	684	6340	1260	589	54.2	134	<2.5	12.2	123
Biochar I.	1500	15850	5270	1780	1950	326	6.08	35.5	319
Biochar II.	1630	16260	4090	1590	1090	315	5.38	33.7	206
Mean_Hull	693	6500	1280	589	57.1	132.5	<2.5	12.25	128
Mean_Biochar	1565	16055	4680	1685	1520	320.5	5.73	34.6	262.5

Data measured in dry matter (DM); unit: mg/kg.

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4.5. Effects of fertilizers and treatment blocks on rice yield and water productivity

Overall, there was no significant differences ($p > 0.05$) found on the average rice yield (RY) for the fertilizer treatments. However, significant differences ($p = 0.009$) were found on the fertilizer treatments between two treatment blocks. A Tukey post-hoc test revealed that fertilizer treatment at block 2 resulted in higher yield on average of 2.89 t/ha over block 1. A groupwise comparison showed highest yield gain (15.2 t/ha) at block 2, T4 (Figure 6), suggesting combined fertilizer (CF) and RHB in this treatment was most advantageous on RY under the experimental conditions.

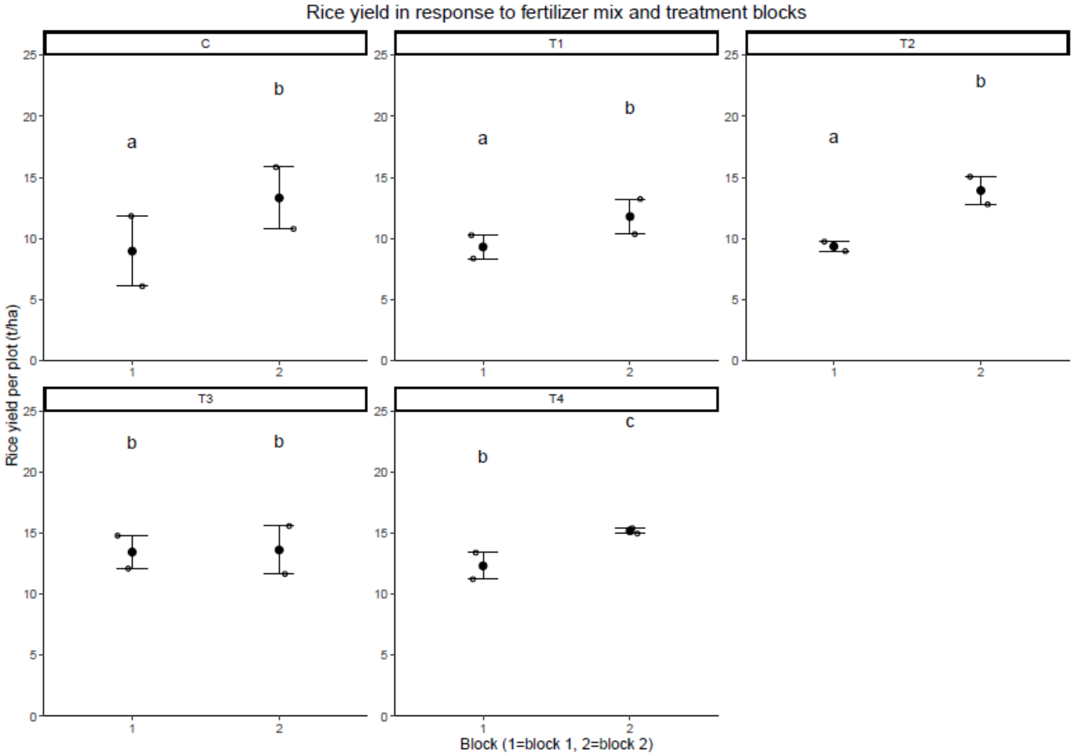

Figure 6: Rice yield (RY) response to fertilizers and treatment blocks. a represents RY ≤10 t/ha per plot; b represents RY between 11-14 t/ha per plot; c represents RY ≥15 t/ha per plot.

The effect of fertilizer and treatment blocks on water productivity (WP) also showed no significant differences ($p > 0.05$). However, significant differences ($p = 0.009$) were found on the fertilizer treatments between two treatment blocks. A Tukey post-hoc test revealed that fertilizer treatment at block 2 resulted in higher WP on average of 45.02 kg/m^3 over block 1. A groupwise comparison showed highest WP (237 kg/m^3) at block 2, T4 (Figure 7), suggesting CF with RHB was most advantageous for improving WP under the experimental conditions. This is followed by T2, block

2 with an average WP of 217 kg/m^3, suggesting the efficiency of RHB and inorganic fertilizer to enhance water availability for rice yield.

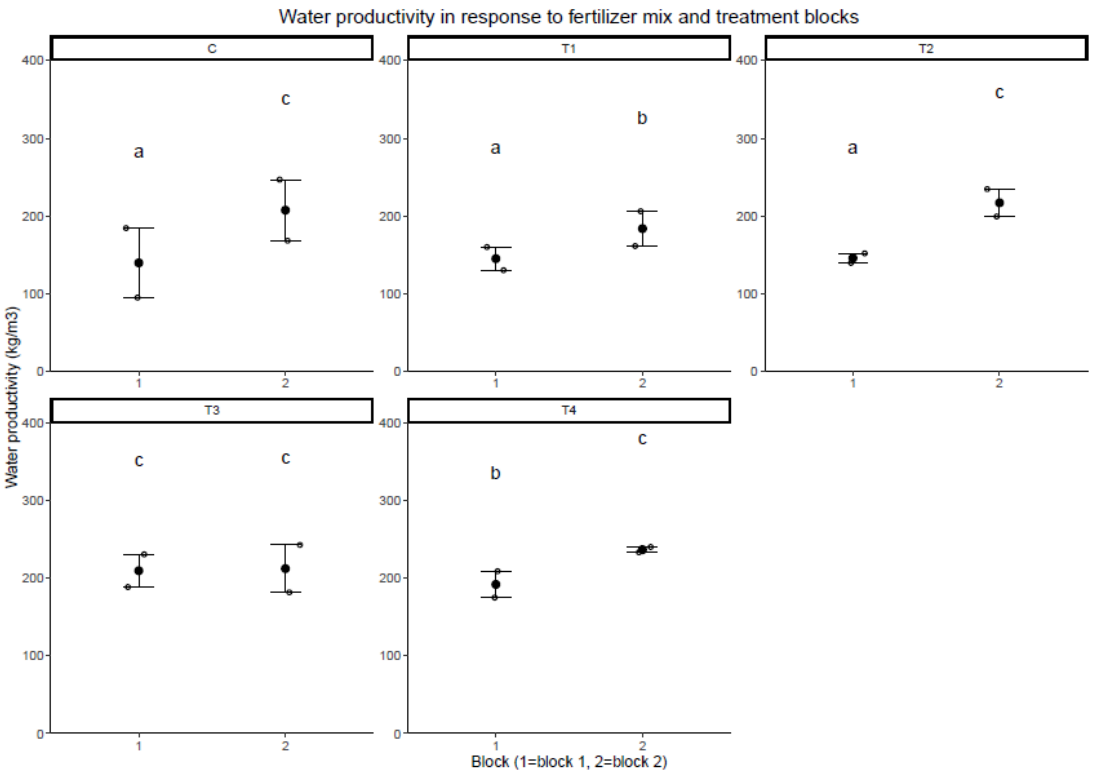

Figure 7: Water productivity (WP) response to fertilizers and treatment blocks. a represents WP ≤150 kg/m^3; b represents WP between 151-200 kg/m^3; c represents WP ≥201 kg/m^3.

4.6. Effects of fertilizers and treatment blocks on rice growth, biomass, TGW, HRP and BGP

Overall, the application of CF showed significant differences ($p < 0.05$) on the rice growth. There was no statistically significant difference ($p > 0.05$) found on the fertilizer treatment in two treatment blocks. A Tukey post-hoc test revealed the highest average panicle length of rice at T4 (73.2 cm) over C (66 cm), suggesting CF and RHB in this treatment was most advantageous on rice growth under the experimental conditions (Table 5). On the other hand, average rice grain biomass per plot was shown significantly higher in fertilizer treatment at block 2 ($p < 0.05$) with an average of 0.83 t/ha over block 1. Groupwise comparison showed the highest grain biomass per plot at block 2, T4, suggesting this treatment as most advantageous for rice grain biomass (Table 5). The second highest grain biomass per plot was found at block 2, T2, suggesting significance of inorganic fertilizer and RHB on rice growth. Similarly, the average rice sheaves biomass per plot was found significantly higher ($p < 0.05$) at block 2, T4, with an average of 1.35 t/ha over block 1 (Table 5). There were no significant differences ($p > 0.05$) found on the average thousand-grain weight of paddy (TGWp) and cargo (TGWc), head rice percentage (HGP), and broken grain percentage (BGP) in all the fertilizer treatment in the two treatment blocks (Table 5).

Table 5: Rice panicle length, biomass, TGWp, TGWc, HRP, BGP, and WP under fertilizer treatments in two treatment blocks.

Fertilizer treatments	**Treatment blocks**	**Panicle length (cm)**	**Grain biomass per plot (t/ha)**	**Rice Sheaves biomass per plot (t/ha)**	**TGWp (g)**	**TGWc (g)**	**HRP (%)**	**BGP (%)**
C	1	66.0*	2.58	8.61	23.0	74.1	60.2	2.7
	2	66.9*	3.82	10.1	22.3	72.7	62.7	2.4
T1	1	70.0	2.68	9.62	22.0	73.2	57.9	2.8
	2	69.5	3.39	10.1	21.9	72.7	62.4	3.2
T2	1	70.3	2.69	9.48	21.9	72.6	60.3	2.7
	2	69.6	4.00*	11.7	22.2	73.2	58.8	2.4
T3	1	69.8	3.86	10.9	22.6	73.3	61.9	2.4
	2	70.3	3.91	10.8	22.0	72.8	58.9	2.8
T4	1	70.3*	3.54	9.69	22.3	73.9	62.6	2.6
	2	73.2*	4.36*	12.2*	22.3	73.1	61.0	3.0

* Significant at $p < 0.05$.

4.7. Correlations between SPAD, vegetation and water index for Minolta chlorophyll meter, spectrometer, and UAV under two treatment blocks

Overall, a strong positive and medium positive correlation was found between SPAD value, NDVI, NDRE, GNDVI, BNDVI and WBI using three plant measuring instruments (Minolta, spectrometer, and UAV) in both treatment blocks (Table 6). SPAD value from Minolta showed strong positive correlation with RENDVI spectrometer in treatment block 1 and 2 (0.82 and 0.70, $p < 0.001$, respectively), and NDRE spectrometer in treatment block 1 (0.76, $p < 0.001$) (Table 6). SPAD values from Minolta in both treatment blocks showed strong correlation (0.89, $p < 0.001$), suggesting that the fertilizer application in both treatment blocks were applied constantly with minor differences.

The vegetation indices calculated using UAV were found to have strong and medium positive correlations in most of the variables between NDVI, NDRE, GNDVI and BNDVI in both treatment blocks. NDVI measured using UAV showed medium correlation with NDRE spectrometer (0.42, $p < 0.05$) in block 1, and SPAD Minolta (0.42, $p < 0.05$) and NDRE spectrometer in block 2 (0.45, $p < 0.05$) (Table 6). Similarly, NDRE UAV showed medium correlation with NDVI, RENDVI, and NDRE spectrometer (0.53, $p < 0.01$; 0.58, $p < 0.001$; 0.62, $p < 0.001$, respectively) in block 1, and RENDVI and NDRE spectrometer (0.49, $p < 0.01$; 0.58, $p < 0.001$, respectively) in treatment block 2 (Table 6). This suggests the efficacy of using UAV-based imaging to determine plant health condition compared to using hand-held Minolta and SpectraVue leaf spectrometer.

The vegetation indices measured using spectrometer showed high correlation between RENDVI and NDRE in both treatment blocks (0.99 and 0.85, $p < 0.001$, respectively) (Table 6), indicating strong effect of these two indices to determine plant health conditions. A strong correlation was also found between NDVI and RENDVI (0.86, $p < 0.001$), NDVI and NDRE (0.89, $p < 0.001$) in treatment block 1, and NDVI and NDRE (0.72, $p < 0.001$) in treatment block 2, using spectrometer as the measuring equipment (Table 6). On the other hand, NDRE spectrometer was shown to have strong correlation with SPAD value using Minolta (0.77, $p < 0.001$) and RENDVI spectrometer (0.81, $p < 0.001$) in treatment block 2 (Table 6).

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Table 6: Correlations between SPAD, NDVI, NDRE, GNDVI, BNDVI, RENDVI and WBI using Minolta, UAV, and spectrometer in two treatment blocks.

Variables		Block 1									Block 2								
		SPAD_ Minolta	NDVI_ UAV	NDRE_ UAV	GNDVI_ UAV	BNDVI_ UAV	NDVI_ spectro	RENDVI_ spectro	WBI_ spectro	NDRE_ spectro	SPAD_ Minolta	NDVI_ UAV	NDRE_ UAV	GNDVI_ UAV	BNDVI_ UAV	NDVI_ spectro	RENDVI_ spectro	WBI_ spectro	NDRE_ spectro
Block 1	SPAD_Minolta	1.00																	
	NDVI_UAV	0.45*	1.00																
	NDRE_UAV	0.68***	0.85***	1.00															
	GNDVI_UAV	0.39*	0.90***	0.88***	1.00														
	BNDVI_UAV	0.04	0.85***	0.60***	0.89***	1.00													
	NDVI_spectro	0.59***	0.38*	0.53**	0.21	-0.00	1.00												
	RENDVI_spectro	0.82***	0.38*	0.58***	0.22	-0.07	0.86***	1.00											
	WBI_spectro	-0.10	-0.13	-0.35	-0.20	-0.06	-0.63***	-0.41*	1.00										
	NDRE_spectro	0.76***	0.42*	0.62***	0.26	-0.02	0.89***	0.99***	-0.52**	1.00									
Block 2	SPAD_Minolta	0.89***	0.42*	0.67***	0.33	-0.02	0.63***	0.81***	-0.17	0.77***	1.00								
	NDVI_UAV	0.50**	0.87***	0.83***	0.82***	0.71***	0.31	0.46**	-0.16	0.50**	0.44*	1.00							
	NDRE_UAV	0.63***	0.74***	0.91***	0.79***	0.53**	0.48**	0.62***	-0.40*	0.66***	0.62***	0.90***	1.00						
	GNDVI_UAV	0.36*	0.78***	0.80***	0.91***	0.80***	0.19	0.27	-0.28	0.32	0.28	0.89***	0.88***	1.00					
	BNDVI_UAV	0.15	0.80***	0.63***	0.86***	0.92***	0.02	0.08	-0.13	0.13	0.05	0.86***	0.70***	0.92***	1.00				
	NDVI_spectro	0.21	0.18	0.34	0.06	-0.08	0.50**	0.46*	-0.58***	0.51**	0.41*	0.24	0.37*	0.08	-0.03	1.00			
	RENDVI_spectro	0.70***	0.34	0.49**	0.13	-0.10	0.64***	0.83***	-0.27	0.81***	0.81***	0.44*	0.54**	0.16	0.03	0.71***	1.00		
	WBI_spectro	0.07	-0.05	-0.26	-0.20	-0.12	-0.28	-0.13	0.83***	-0.23	-0.01	-0.10	-0.32	-0.28	-0.17	-0.58***	-0.15	1.00	
	NDRE_spectro	0.68***	0.45*	0.58***	0.23	0.02	0.72***	0.85***	-0.37*	0.85***	0.79***	0.52**	0.61***	0.26	0.13	0.75***	0.98***	-0.24	1.00

*** Significant at $p < 0.001$. ** Significant at $p < 0.01$. * Significant at $p < 0.05$. Dark green: strong positive correlation. Light green: medium positive correlation.

Comparing the vegetation indices using chlorophyll meter, spectrometer and UAV in different rice growth stages, correlation analysis showed medium to strong correlations during the panicle initiation, flowering, and ripening stage. In panicle initiation stage, medium correlation was found between SPAD Minolta and NDRE UAV (0.64, $p < 0.05$) (Table 7). While in flowering stage, a strong correlation was found between SPAD Minolta and NDRE UAV (0.73), and SPAD Minolta and GNDVI UAV (0.73) (Table 8). Similarly, strong correlation was found during the ripening stage between SPAD Minolta and NDRE UAV (0.72, $p < 0.05$), SPAD Minolta and GNDVI UAV (0.71, $p < 0.05$), and SPAD Minolta and RENDVI spectrometer (0.73, $p < 0.05$) (Table 9).

Table 7: Correlations between SPAD, NDVI, NDRE, GNDVI, BNDVI, RENDVI and WBI in the rice panicle initiation stages.

	SPAD_ Minolta	NDVI_ UAV	NDRE_ UAV	GNDVI_ UAV	BNDVI_ UAV	NDVI_ spectro	RENDVI_ spectro	WBI_ spectro	NDRE_ spectro
SPAD_Minolta	1.00								
NDVI_UAV	0.41	1.00							
NDRE_UAV	0.64*	0.90**	1.00						
GNDVI_UAV	0.59	0.93**	0.99**	1.00					
BNDVI_UAV	0.26	0.96**	0.84**	0.88**	1.00				
NDVI_spectro	-0.43	-0.58	-0.58	-0.58	-0.48	1.00			
RENDVI_ spectro	0.15	-0.10	0.22	0.15	-0.19	0.14	1.00		
WBI_spectro	0.08	-0.02	-0.00	0.04	0.02	-0.10	-0.28	1.00	
NDRE_spectro	0.20	-0.09	0.22	0.15	-0.21	0.11	0.97**	-0.42	1.00

* Significant at $p < 0.05$. ** Significant at $p < 0.01$.

Table 8: Correlations between SPAD, NDVI, NDRE, GNDVI, BNDVI, RENDVI and WBI in the rice flowering stages.

	SPAD_ Minolta	NDVI_ UAV	NDRE_ UAV	GNDVI_ UAV	BNDVI_ UAV	NDVI_ spectro	RENDVI_ spectro	WBI_ spectro	NDRE_ spectro
SPAD_Minolta	1.00								
NDVI_UAV	0.30	1.00							
NDRE_UAV	0.73*	0.47	1.00						
GNDVI_UAV	0.73*	0.46	0.98**	1.00					
BNDVI_UAV	0.43	0.69*	0.68*	0.73*	1.00				
NDVI_spectro	0.37	0.41	0.02	-0.04	-0.04	1.00			
RENDVI_spectro	0.51	0.40	0.38	0.33	0.18	0.79**	1.00		
WBI_spectro	-0.25	-0.72*	-0.10	-0.12	-0.48	-0.57	-0.33	1.00	
NDRE_spectro	0.57	0.47	0.50	0.45	0.25	0.76*	0.98**	-0.38	1.00

* Significant at $p < 0.05$. ** Significant at $p < 0.01$.

Table 9: Correlations between SPAD, NDVI, NDRE, GNDVI, BNDVI, RENDVI and WBI in the rice ripening stages.

	SPAD_ Minolta	NDVI_ UAV	NDRE_ UAV	GNDVI_ UAV	BNDVI_ UAV	NDVI_ spectro	RENDVI_ spectro	WBI_ spectro	NDRE_ spectro
SPAD_Minolta	1.00								
NDVI_UAV	0.55	1.00							
NDRE_UAV	0.72*	0.95**	1.00						
GNDVI_UAV	0.71*	0.92**	0.99**	1.00					
BNDVI_UAV	0.47	0.78**	0.77**	0.81**	1.00				
NDVI_spectro	0.34	0.32	0.24	0.19	-0.08	1.00			
RENDVI_spectro	0.73*	0.62	0.66*	0.62	0.22	0.82**	1.00		
WBI_spectro	-0.03	-0.15	-0.01	0.06	0.31	-0.89**	-0.62	1.00	
NDRE_spectro	0.72*	0.59	0.63	0.59	0.20	0.82**	1.00**	-0.64*	1.00

* Significant at $p < 0.05$. ** Significant at $p < 0.01$.

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4.8. PCA of vegetation indices variables between treatment blocks

The principal component analysis (PCA) showed the correlation between each targeted vegetation indices measured using Minolta, UAV, and spectrometer in two treatment blocks (Figure 8). A strong correlation was found in grouping variables of SPAD Minolta, and NDVI, NDRE, RENDVI spectrometer in both treatment block 1 and 2 (Figure 8), indicating a strong positive correlation of these vegetation indices using Minolta and spectrometer in determining plant health conditions under different fertilizer combinations in the treatment blocks. A very strong positive correlation was also observed between all the vegetation indices (NDVI, NDRE, BNDVI, GNDVI) measured using UAV in both the treatment blocks, with all the targeted variables grouped together (Figure 8). It was observed that GNDVI UAV block 1, BNDVI UAV block 2, and GNDVI UAV block 2 were the top three variables contributing the most to the dimensions 1 and 2 in the dataset (Figure 9), suggesting the efficiency of UAV under these parameters to determine plant health condition. On the other hand, water band index (WBI) measured using spectrometer in both treatment groups was observed on the opposite side of the plot (Figure 8), indicating a negatively weak correlation of these variables to the other variables under experimental conditions. WBI spectrometer in block 2 also showed lowest cos2 value compared to block 1 (Figure 8), suggesting low representation of WBI values in this block to determine plant health conditions under the experimental conditions.

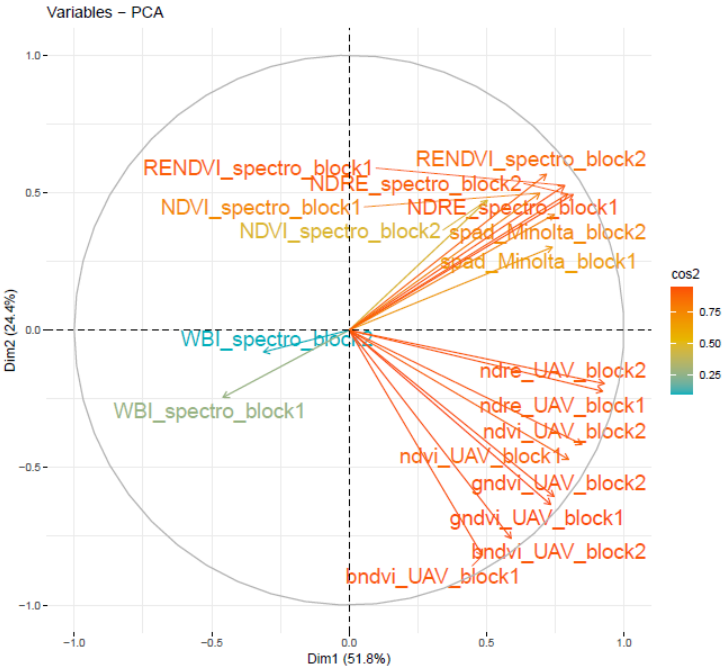

Figure 8: Principal component analysis of SPAD, vegetation and water indices using UAV, Minolta, and spectrometer in two fertilizer treatment blocks.

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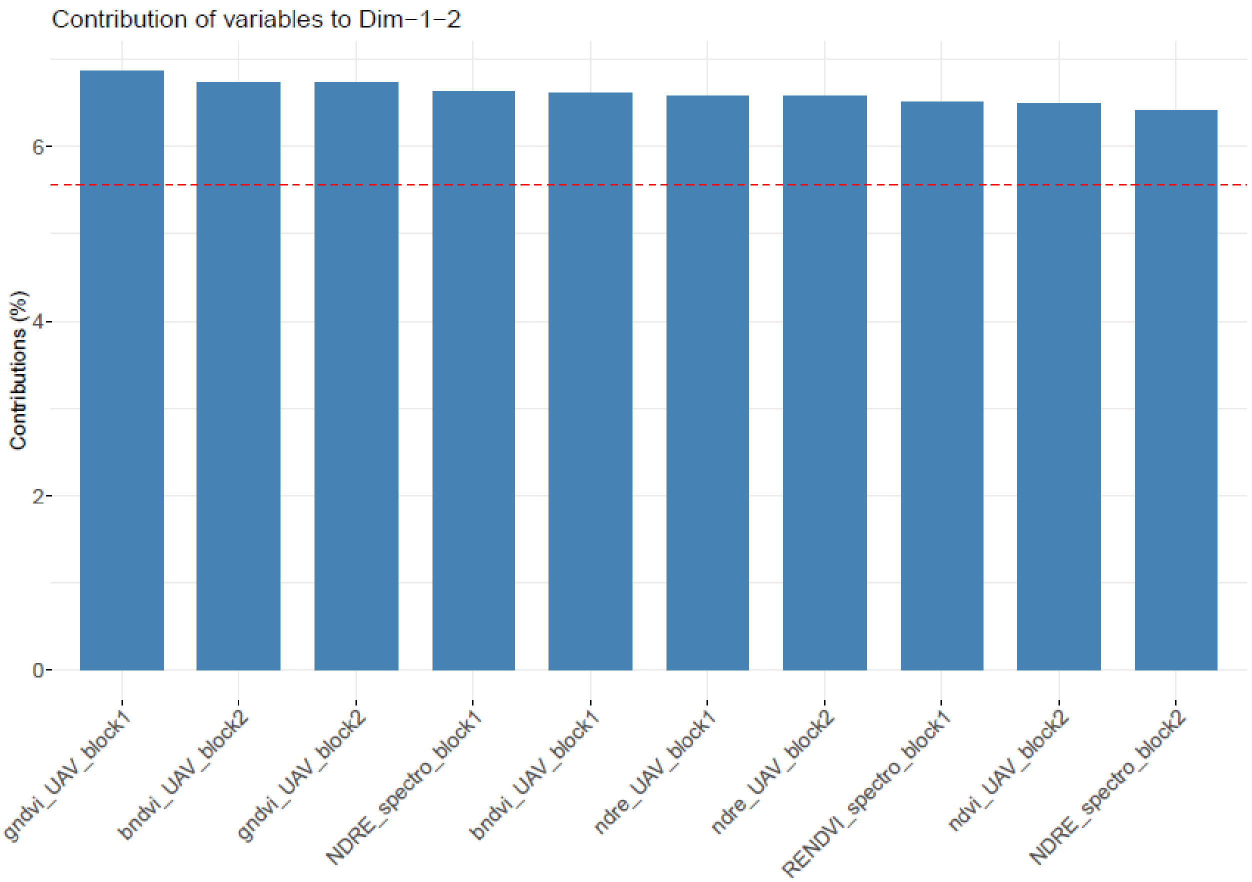

Figure 9: Total contribution of each variable to dimensions 1 and 2. The red dashed line indicates the expected average contribution.

4.9. Effects of fertilizers and treatment blocks at different rice growth stages on plant chlorophyll content

Overall, the average SPAD values were shown higher during heading and flowering growth stage compared to other growth stages in both the fertilizer treatment blocks (Figure 10). This is followed by booting and heading, panicle initiation, ripening stage 1, tillering, and ripening stage 2, in a decreasing order of the SPAD values (Figure 10). In both treatment blocks, treatment T2, T3 and T4 showed higher average SPAD values (45.3 and 44.6 in block 1 and 2 respectively) compared to C (43.8 and 44.2 in block 1 and 2 respectively) and T1 (44.2 and 44.3 in block 1 and 2 respectively) (Figure 10), suggesting the efficiency of these fertilizer combinations on plant health and growth.

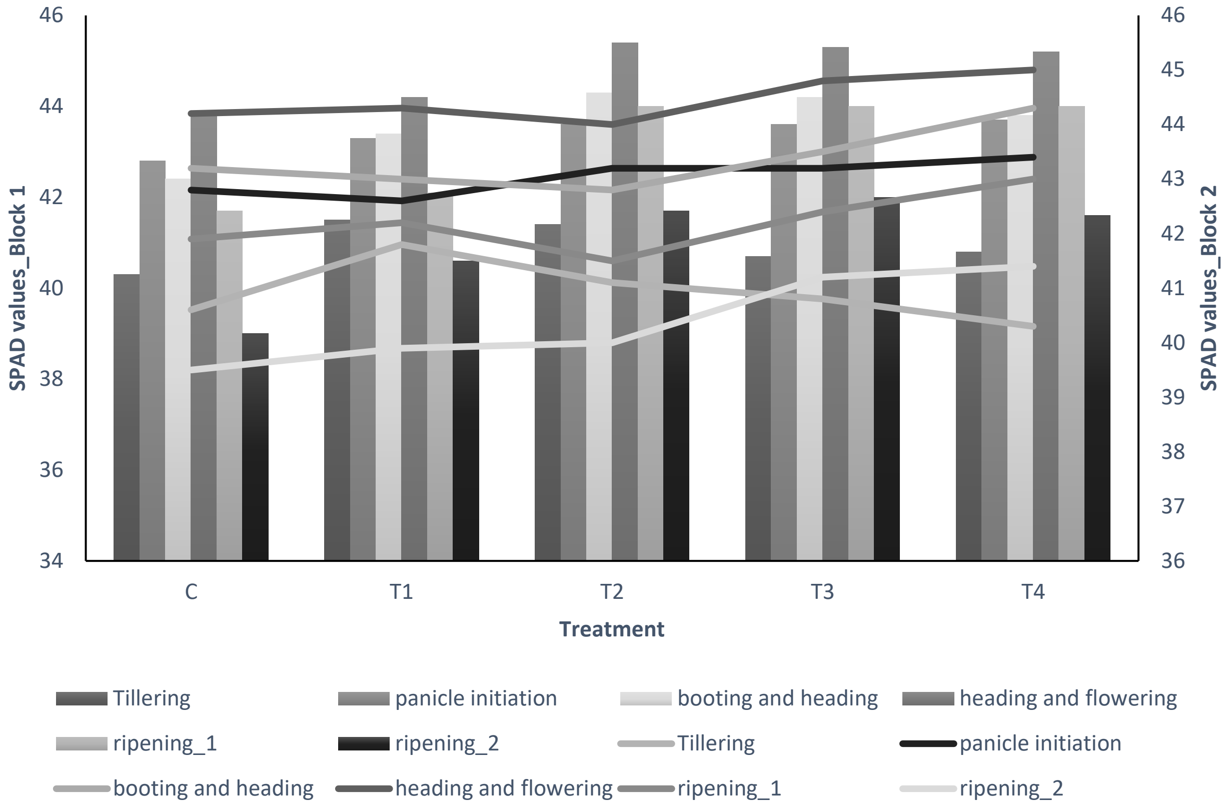

Figure 10: Effect of fertilizer and treatment blocks on SPAD values under different rice growth stages (tillering, panicle initiation, booting and heading, heading, and flowering, ripening 1, ripening 2). Block 1 represented by 'bar' plot and block 2 represented by 'line' plot.

4.10. Effects of fertilizers and treatment blocks on grain quality

Analysis on rice grain quality showed no significant difference ($p > 0.05$) on the grain length and length-width ratio (LWR) for all treatment fertilizers in both treatment blocks (Table 10). However, significant differences were found on the grain width between T1 and C ($p = 0.04$), and T2 and C ($p = 0.04$) in both the treatment blocks (Table 10), suggesting the importance of inorganic fertilizer and RHB in T2 on rice grain quality. Overall, the mean grain width in C (36.0 mm) was greater compared to T2 (34.65 mm) and T1(34.6 mm) in block 1 and 2 (Table 10). Images captured using SmartGrain software on rice grain samples' length, width, and length-width ratio (LWR) of C (top), T1 (middle) and T2 (bottom) in treatment block 1 (a) and 2 (b), were presented in Figure 11.

Table 10: Mean length, width, and length-width ratio (mm) of rice grain for each fertilizer in two treatment blocks.

Fertilizer	Treatment blocks	Length (mm)	Width (mm)	Length-width ratio (LWR)
C	1	95.38	35.80*	2.68
	2	95.46	36.29*	2.64
T1	1	94.63	34.10*	2.87
	2	92.21	35.11*	2.64
T2	1	95.20	34.60*	2.79
	2	92.64	34.70*	2.70
T3	1	94.85	35.63	2.68
	2	95.35	35.54	2.70
T4	1	94.75	34.90	2.73
	2	94.13	35.41	2.67

* Significant at $p < 0.05$.

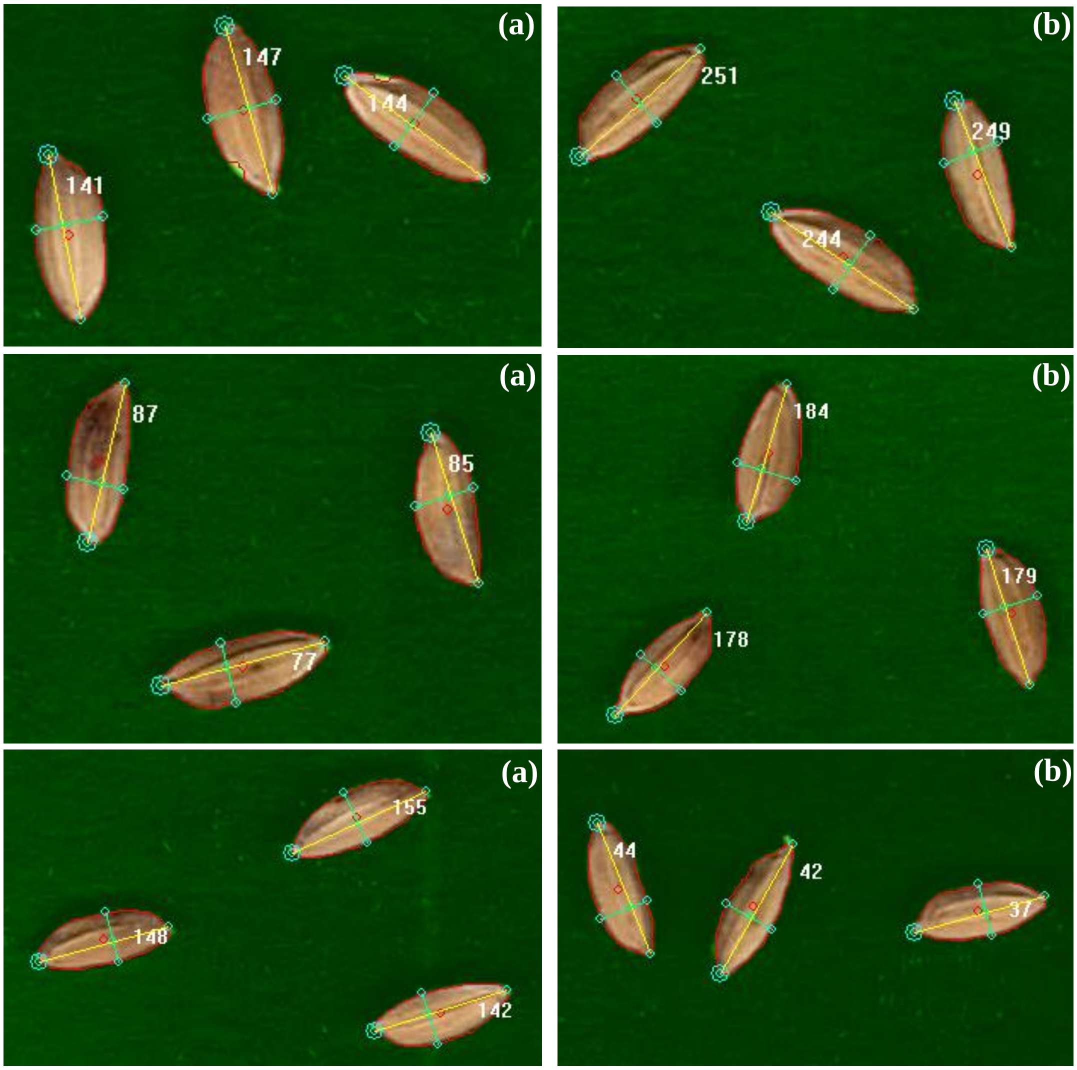

Figure 11: Rice grain samples' length, width, and length-width ratio (LWR) measured using SmartGrain software for C (top), T1 (middle) and T2 (bottom) in treatment block 1 (a) and 2 (b).

4.11. Factors contributing to rice yield, rice growth, grain quality, and water productivity increase in the aerobic rice cultivation

Table 11 showed correlation analyses results between RY, growth, grain quality and WP under fertilizer treatment in two treatment blocks. Strong positive correlation was observed between WP and RY, suggesting an increase on RY in the treatment plot was associated with an increase in WP.

Table 11: Correlations between rice yield, panicle length, grain width and water productivity under combined fertilizer in two treatment blocks.

	Rice yield	Panicle length	Grain width	Water productivity
Rice yield	1.00			
Panicle length	0.46	1.00		
Grain width	0.38	-0.44	1.00	
Water productivity	1.00**	0.46	0.38	1.00

* Significant at $p < 0.05$. ** Significant at $p < 0.01$.

4.12. PCA and correlation between soil properties and rice yield

PCA biplot graph showed that manganese (Mn), copper (Cu), zinc (Zn), and total phosphorous (total P) were in the same direction on the Dim2 axis, indicating these soil nutrients were positively correlated with each other and with RY and soil humus content, that were also on the same axis (Figure 13). On the other hand, other soil properties, including the nitrite-nitrate-N (NO_2^--NO_3^--N), sulfate content, potassium oxide (K_2O), water soluble salt, soil plasticity index, sodium (Na), pH, and carbonated lime were in the opposite direction with Dim2, implying a negative association of these soil properties with RY (Figure 13). From the total contribution of soil properties, it was observed that nine soil properties, from highest to lowest (Cu, Zn, Mn, pH, total P, NO_2^--NO_3^--N, water soluble salt, carbonated lime, and Na), contributed the most to dimensions 1 and 2 in the dataset (Figure 14). Cu, Zn and Mn were the top three contributors affecting RY in the study.

A one-way ANOVA to compare the effect of treatment blocks on soil humus content showed significant differences ($p = 0.02$) between treatment block 1 and 2. Tukey's test revealed treatment block 2 (2.13±0.04) has higher mean soil humus content than block 1 (2.02±0.07) (Figure 12). Correlation analysis between RY and final soil properties showed strong positive correlation ($R = 0.71$) between RY and soil humus under fertilizer treatment in two treatment blocks (Table 12). This suggests that increase in RY in the experimental plots was associated with an increase in the humus content available in the soil and supplied from the fertilizer and RHB application. The analysis also associated well with the results from the PCA graph in Figure 13 which shows positive correlation between RY and soil humus content.

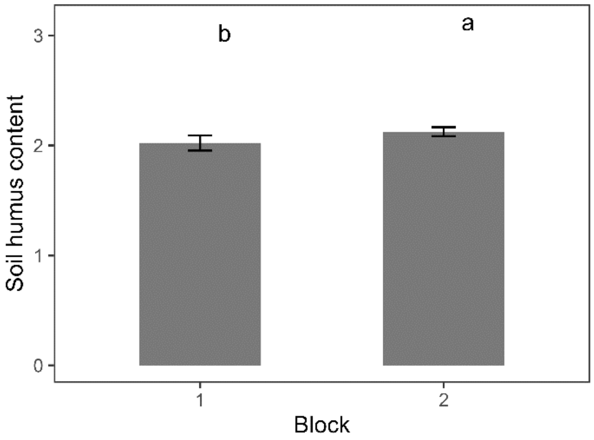

Figure 12: Mean and standard deviation of soil humus content showed significant differences by Tukey's test between treatment block 2 and 1.

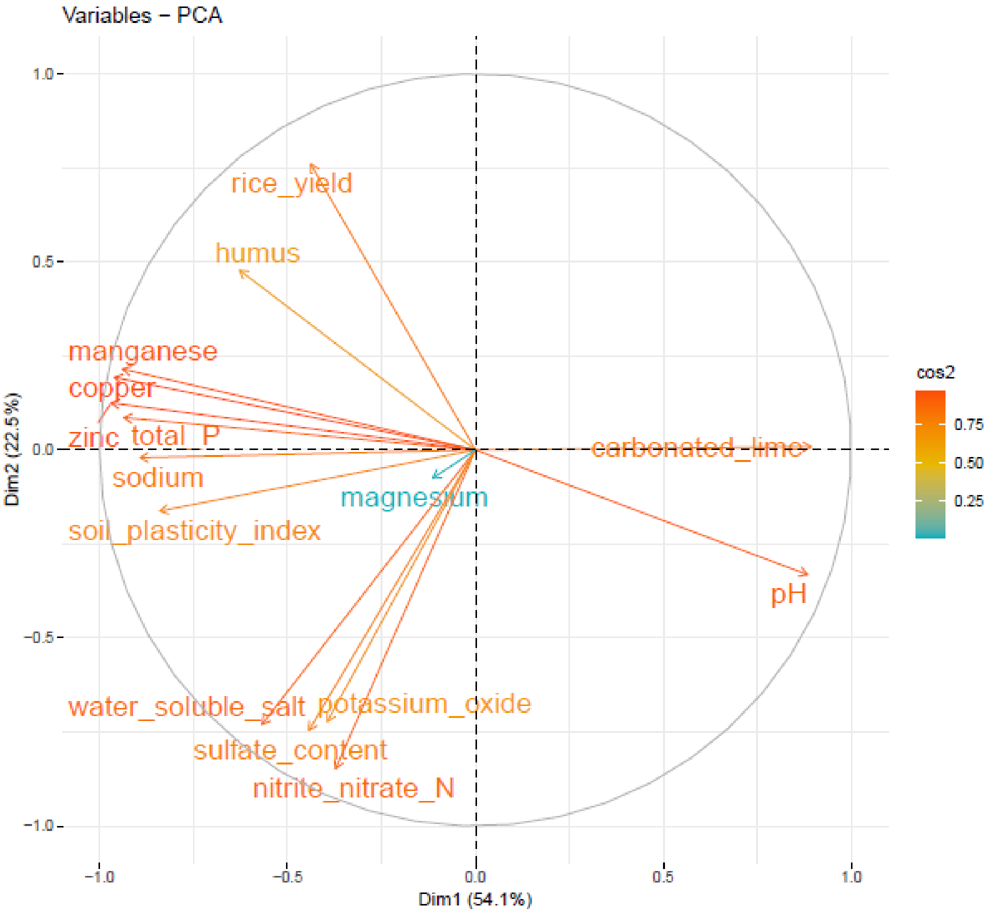

Figure 13: Principal component analysis of soil properties and rice yield in two treatment blocks.

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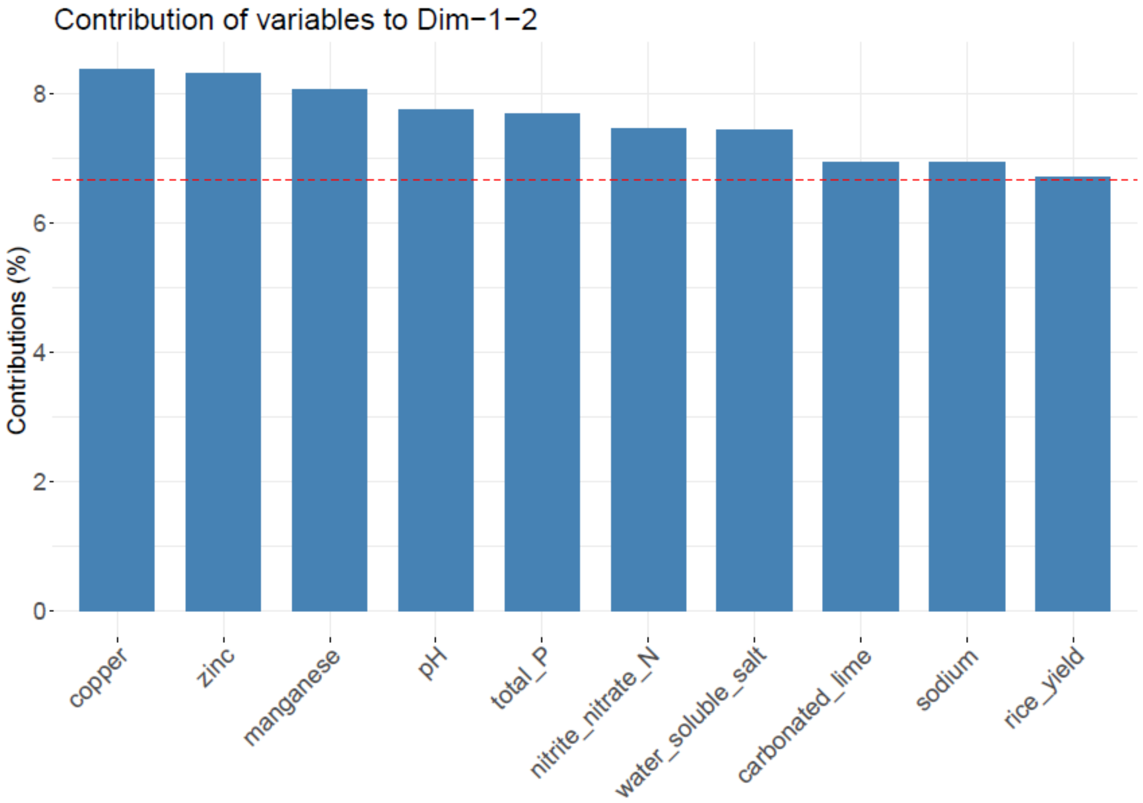

Figure 14: Total contribution of each variable to dimensions 1 and 2. The red dashed line indicates the expected average contribution.

4.13. Crop nitrogen condition based on multispectral and thermal aerial imaging

Based on the correlation analysis between SPAD values, vegetation, and water index, NDRE UAV and GNDVI UAV showed a medium to strong correlation with SPAD Minolta during the rice panicle initiation, flowering, and ripening stages. Figure 15 showed multispectral images of NDVI, NDRE and GNDVI UAV, which reflected the rice leaf nitrogen content in the treatments. The correlation between fertilizer treatment block 1 and 2 showed medium correlation between NDVI UAV and NDRE spectrometer in block 1, as well as NDVI UAV with SPAD Minolta and NDRE spectrometer in block 2. Simply, the results in this study suggested the efficiency of using UAV-based imaging, particularly NDVI, NDRE and GNDVI values, in determining plant health conditions. During analysis of the thermal images, no significant temperature differences were found among the analyzed rice varieties. However, it was important to note that the results can be refined by increasing the frequency of measurements and choosing a more appropriate time for thermal imaging.

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Table 12: Correlations between rice yield and final soil properties under fertilizer combinations in two treatment blocks.

	Rice yield	pH	SPI	Water soluble salt	Carbonated lime	Humus	Nitrite-nitrate-N	Total P	K_2O	Na	Cu	Mn	Zn	Sulfate content	Mg
Rice yield	1.00														
pH	-0.64*	1.00													
SPI	0.21	-0.65*	1.00												
Water soluble salt	-0.27	-0.25	0.62	1.00											
Carbonated lime	-0.40	0.82**	-0.57	-0.42	1.00										
Humus	0.71*	-0.58	0.61	0.09	-0.45	1.00									
Nitrite-nitrate-N	-0.35	-0.07	0.42	0.87**	-0.39	-0.08	1.00								
Total P	0.39	-0.91**	0.70*	0.46	-0.85**	0.46	0.20	1.00							
K_2O	-0.51	-0.12	0.42	0.68*	-0.36	-0.19	0.62	0.43	1.00						
Na	0.47	-0.74*	0.63	0.48	-0.88**	0.50	0.36	0.82**	0.29	1.00					
Cu	0.50	-0.92**	0.81**	0.43	-0.81**	0.69*	0.15	0.95**	0.30	0.78**	1.00				
Mn	0.45	-0.90**	0.75*	0.34	-0.86**	0.64*	0.11	0.94**	0.28	0.79**	0.97**	1.00			
Zn	0.46	-0.86**	0.83**	0.46	-0.83**	0.67*	0.20	0.93**	0.32	0.84**	0.98**	0.97**	1.00		
Sulfate content	-0.23	-0.07	0.55	0.76*	-0.42	0.06	0.88**	0.21	0.52	0.52	0.20	0.19	0.32	1.00	
Mg	0.18	-0.27	0.01	0.13	-0.09	-0.31	0.16	0.18	-0.10	0.29	0.03	-0.04	0.01	0.14	1.00

* Significant at $p < 0.05$. ** Significant at $p < 0.01$. SPI = Soil Plasticity Index according to Arany.

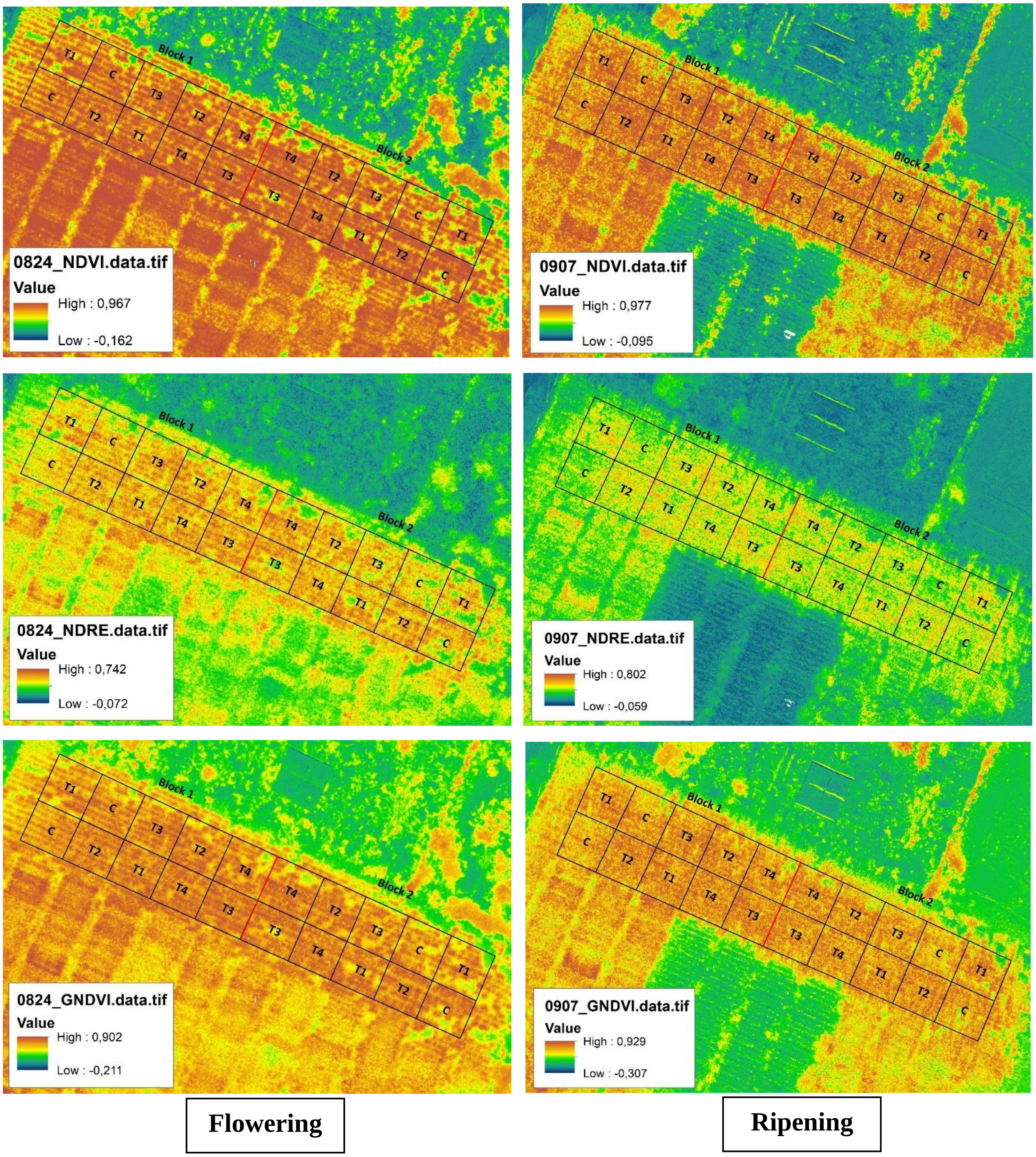

Figure 15: Multispectral images of NDVI (top), NDRE (middle) and GNDVI (bottom) in the treatment groups during flowering and ripening stages.

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5. DISCUSSION

5.1. Rice yield, growth, soil properties, grain quality and water productivity response to fertilizer and treatment blocks

Generally, RY was shown higher in the treatment with CF and RHB (T4 and T3) compared to the treatment applying only inorganic fertilizers (T1 and T2) and the control treatment. The average panicle length was also found higher in the CF with RHB than the latter. Besides that, correlation analysis showed strong correlation ($R = 0.71$) between RY and soil humus content, indicating the contribution of CF and RHB in the treatment group. It was also discovered that nutrients important for crop growth, such as Mn, Cu, Zn, and total P were positively correlated with RY and soil humus content, suggesting the role of RHB to store, and thus increase nutrients in the soil (Nair et al., 2017). These further suggest the benefits of CF and RHB to increase aerobic RY under the experimental conditions. There are advantages of mixing inorganic and organic fertilizers to improve soil fertility and health, leading to an increase in RY (Ahmad et al., 2016; Arif et al., 2014). Studies have suggested that the combination of fertilizers could help to increase soil microbial activity and improve soil properties, thus helping to solve issues of degraded soil fertility and quality, and promoting sustainable agricultural production (Anisuzzaman et al., 2021; Bilkis et al., 2017; Ge et al., 2010; Ghosh & Devi, 2019; Kakar et al., 2020; Liu et al., 2021a). In addition, it is also recommended to use CF to improve crop yield as this will help to promote integrated soil fertility management (Pincus et al., 2016), while also understanding that continuous application of chemical fertilizers will result in crop yield reduction, decline in soil health and causing environmental problems in the longer term (Kumar et. al, 2022). As organic fertilizers and rice husk by-products are easily available, farmers could make use of these available ingredients to reduce their farm operation costs while increasing rice production through improving soil health. Studies have also reported that applying organic fertilizer and RHB could help to improve water productivity and nutrient use efficiency from the re-utilization of waste and by-products of living organisms (Gupta et al., 2019; Haefele et al., 2011; Oladele et al., 2019; Orge & McHenry, 2013). In this study, RHB was observed to effectively enhance WP while increasing RY, where WP was found higher in the treatment with CF and RHB (T4 and T2 at block 2 with WP reported at 237 kg/m^3 and 217 kg/m^3 respectively). It was also discovered of a strong relationship between RY and WP, where correlation analysis showed strong correlation between these two parameters. This agrees with the findings from other studies, in which RHB combined with fertilizer help to improve crop yield by enhancing nutrient and water retention due to the high silica content of RHB (Kimetu et al., 2008; Singh Karam et al., 2022; Yeboah et al., 2009; Zanli et al., 2022).

On the other hand, while there were no significant differences found between each fertilizer treatments on RY, this can be explained by low amount of nitrogen (N) applied to the soil, which is important for plant growth, yield, and quality (Ladha et al., 2005; Sarker et al., 2015). The inadequate amount of RHB applied in this study might also cause no significant differences among the fertilizer treatments applied. This is important concerning the evidence revealed on the positive effect of biochar amendment on the soil quality leading to improving RY, with close relationship between the effect of biochar amendment on RY and N use efficiency (Huang et al., 2013). However, interestingly, in this study, significant differences were found on RY, soil properties, WP, rice grain biomass, and grain width between fertilizer treatments in two treatment blocks, with higher values found in block 2 compared to block 1. This could only be explained by past agricultural activity carried out on that specific land area which contains more N than in another part of the land; position of the sun which provides more spectrum required by the plant to carry out photosynthesis; and less disturbances and damages from the insects and pests. These situations could happen in any open field experiment, which are vulnerable to the unexpected weather conditions as affected by the climate change (Ziska et al., 2012), and infestation of insects, pests, and diseases (Aguda et al., 1994; Ane & Hussain, 2015). This is particularly the case happened in Hungary where rice is largely impacted by variable climatic conditions (Jancsó et al., 2017).

5.2. Relationship between rice yield and SPAD, NDVI, GNDVI, RENDVI and NDRE in different rice growth stages

In this study, the use of SPAD chlorophyll meter, spectrometer and UAV has been shown to be able to help determine plant health conditions in different growth stages. This is found from the correlation analysis, with a strong relationship between SPAD meter, NDRE UAV, GNDVI UAV, and RENDVI spectrometer in flowering and ripening stages (Table 8 and 9). Besides that, PCA analysis also showed strong correlation in the grouping variables of SPAD meter, all UAV-derived vegetation indices, and NDVI, NDRE and RENDVI spectrometer in both fertilizer treatment blocks (Figure 8), suggesting the reliability of UAV data compared to the traditional methods.

In addition to UAV, both SPAD meter and spectrometer are powerful traditional hand-held instruments to estimate plant leaf N content and spectral resolution (Cabangon & Tuong, 2011;

Sun et al., 2017), which provide important indicators of plant health, photosynthetic efficiency, and crop productivity (Bussotti et al., 2020). In these days, the use of remote sensing-based mapping using UAV has been accepting wide interest due to its ability to help capturing reflectance values using built-in indices and monitoring crop N status over a large geographic area (Perros et al., 2021; Wang et al., 2021b). The values generated from the device comes from different combinations of wavebands, which provide an estimation of crop biomass or yield (Hatfield et al., 2019). Several important chlorophyll indices related to the leaf chlorophyll content which gives an indirect estimation of crop nutrient status are NDVI, green NDVI (GNDVI) and red edge NDVI (RENDVI) (Hatfield et al., 2008; Hatfield et al., 2019; Perros et al., 2021). These indices are often used to compare and validated with the data collected using hand-held instruments or chemical methods (Székely et al., 2023; Wang et al., 2021a; Wang et al., 2021b).

This study has highlighted the role of UAV aerial imagery in assessing chlorophyll content to determine plant conditions in aerobic rice cultivation. Aerial imagery derived vegetation indices showed medium to strong positive correlations of the vegetation indices between NDRE, GNDVI and NDRE UAV with SPAD Minolta and NDRE spectrometer, at different rice growth stages under various fertilizer treatments. This showed the efficiency of using UAV-based imaging in providing robust measurement of aerobic rice health conditions. The results obtained also proved UAV aerial imagery as a cost-effective, time-saving, and non-destructive monitoring tool to assess crop nitrogen status leading to determination of plant health conditions (Perros et al., 2021; Wang et al., 2021b).

A strong correlation between all the vegetation indices (NDVI, NDRE, BNDVI, GNDVI) measured using UAV was also revealed, suggesting the sensitivity of these indices' wave bands to detect the plant chlorophyll at the plot level, hence determining the plant health status and rice production. This agrees with Liu et al. (2021b), which have found that GNDVI provides the highest accuracy in the rice model with combination of NIR and red light improved estimation accuracy in the models, hence suggesting a combination of the vegetation indices to obtain high accuracy in estimating rice leaf area index.

6. CONCLUSION

This study evaluated the effects of combined fertilizers and rice husk biochar on rice yield, growth, grain quality and water productivity under aerobic rice cultivation in Hungary. The results showed higher rice yield and average panicle length in fertilizer treatment given combined fertilizer with RHB compared to other treatments. Significant differences were observed on rice yield, soil humus content, WP, rice grain biomass, and grain width between fertilizer treatments in the two blocks, with block 2 was found better performed than block 1. There were no significant differences found between each fertilizer treatments on rice yield, which could be explained by low amount of nitrogen (N) applied to the soil. However, important minerals for rice growth, such as Mn, Cu, Zn, and total P were found positively correlated with rice yield and soil humus content, suggesting the role of RHB to store, and thus increase nutrients in the soil layer. SPAD chlorophyll meter, spectrometer and UAV multispectral imagery used in the study has been shown able to help determine plant health conditions in different aerobic rice growth stages, with a strong correlation found between SPAD meter, NDRE UAV, GNDVI UAV, and RENDVI spectrometer in flowering and ripening stages. A strong correlation was found between all the vegetation indices (NDVI, NDRE, BNDVI, GNDVI) measured using UAV. PCA results also showed GNDVI UAV in both treatment blocks 1 and 2 provide best representation of crop health and nitrogen (N) content compared to SPAD meter and spectrometer. Hence, the findings from this study suggest combined fertilizer and RHB to increase rice yield, growth, grain quality and improve WP for sustainable aerobic rice cultivation in Hungary. UAV aerial imagery serves as a promising monitoring tool, helping to saves time and energy while also providing sensitive and accurate results in monitoring plant nitrogen status, health, and yield over a wide range of geographic area, compared to the traditional and time-consuming measurement using SPAD meter and spectrometer. Under the experimental condition, the results in this study underscore the significance of UAV-based imaging in assessing plant health, chlorophyll content, and other parameters crucial for understanding crop growth and yield in aerobic rice cultivation. The positive correlations and comparisons with the traditional instruments have highlighted the potential and reliability of UAVs in precision agriculture. Therefore, further studies are recommended in integrated nutrient and crop management of aerobic rice by varying the amount of fertilizer and RHB applied and to achieve better precision, the number of measuring frequencies for thermal and multispectral imaging could be increased and used GNDVI indices to determine RY in different growth stages.

7. SUMMARY

Rice is the staple food for more than half of the world's population. The quality and production of rice depends on soil available nutrients and is usually supplied through fertilizers. Continuous application of inorganic fertilizer was found to decrease soil productivity and affect crop yield and soil health in the long term. However, combined inorganic and organic fertilizers have been widely recommended, especially on degraded soils, to improve soil fertility. This study aimed to evaluate the efficiency of combined fertilizers (CF) and rice husk biochar (RHB) to improve aerobic rice yield (RY), soil properties, grain quality, and WP in Hungary. A field experiment was carried out from April to September 2023 at the Lysimeter station of the Research Centre of Irrigation and Water Management in Szarvas, MATE. Five treatments, with and without CF and RHB at different rates (50 kg N/ha and 100 kg N/ha NPK 15:15:15; 3 L/m^2 organic fertilizer; 1 t/ha RHB) were applied in a randomized block design with two replications each in 2 blocks, and a total of 20 plots. A rice variety known as 'M 488' was used and drip irrigation was applied at an initial rate of 1 L/m^2 per day. The study utilizes SPAD chlorophyll meter, SpectraVue leaf spectrometer, and UAV-based imaging to assess the effects of fertilizer treatments on plant health, yield, growth, and WP. The results showed higher RY in treatment given CF with RHB (T4) compared to other treatments. Significant differences were observed on RY, soil humus content, WP, grain biomass, and grain width between fertilizer treatments in two treatment blocks, with block 2 was found better performed than block 1. Mn, Cu, Zn, and total P were found positively correlated with RY and soil humus content, suggesting the role of RHB to store, and thus increase nutrients in the soil layer. A strong positive correlation was found between SPAD meter, NDRE UAV, GNDVI UAV, and RENDVI spectrometer in flowering and ripening stages. PCA results also showed GNDVI UAV in both treatment blocks 1 and 2 provide best representation of crop health and nitrogen (N) content compared to SPAD meter and spectrometer. The findings from this study have found CF and RHB to increase RY and growth, and improve grain quality, soil properties and WP of aerobic rice in Hungary. UAV aerial imagery serves as a promising monitoring tool, helping to save time and energy while providing sensitive and accurate results in monitoring plant N status, health, and yield over a wide range of geographic area. Further studies are recommended in integrated nutrient and crop management of aerobic rice by varying the amount of fertilizer and RHB applied, and to use GNDVI indices to determine RY in different growth stages using remote sensing method.

Keywords: aerobic rice, fertilizer, rice husk biochar, yield, water productivity, remote sensing

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10. APPENDICES

Appendix 1: Preparation of organic fertilizer (top); Rice plant measurement using a measuring tape (mid-left), SPAD chlorophyll meter (mid-middle), and SpectraVue leaf spectrometer (mid-right); UAV devices used in taking the multispectral and thermal images of rice (bottom).

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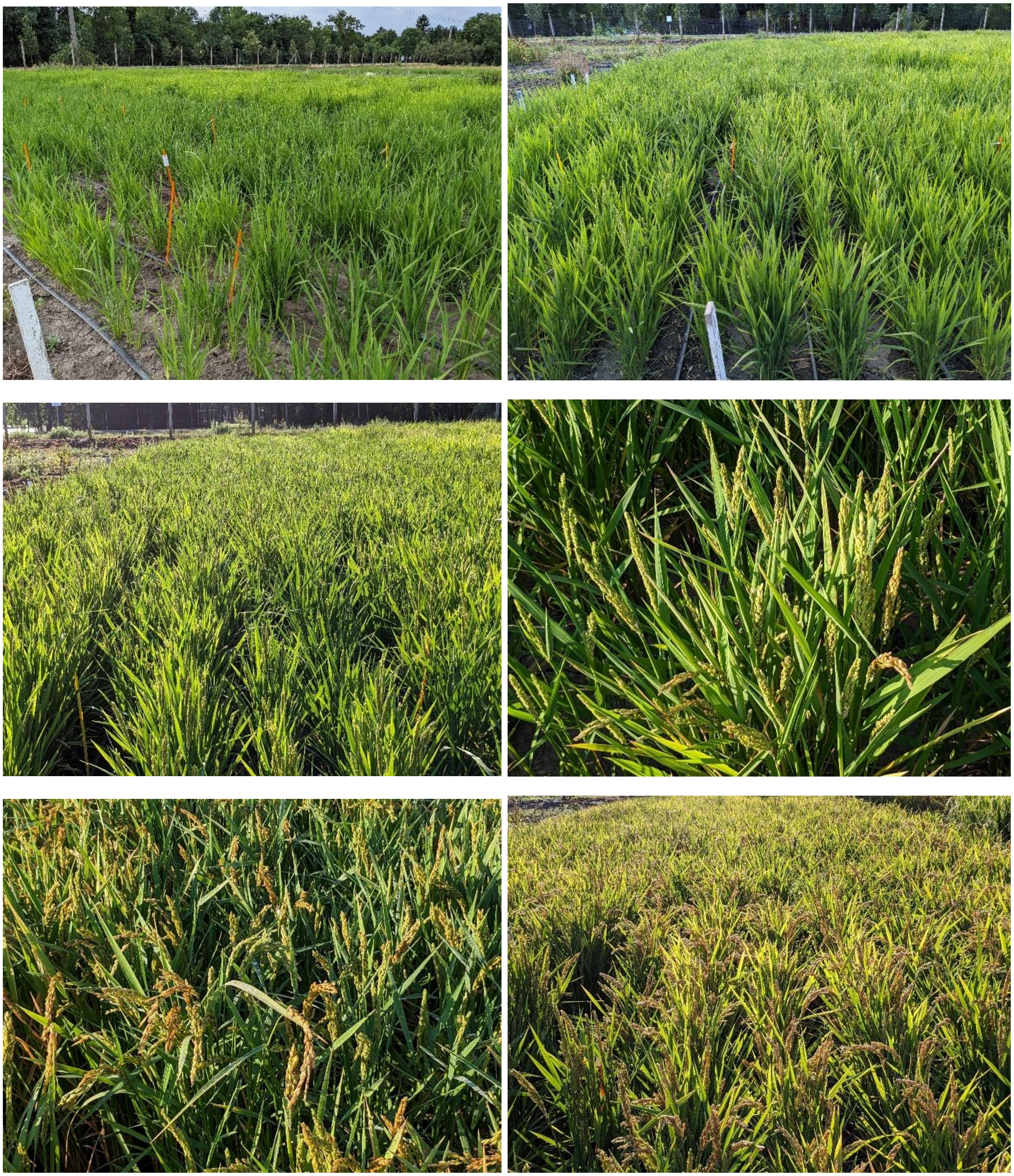

Appendix 2: Aerobic rice growth stages. Tillering (top left); panicle initiation (top right); booting and heading (middle left); heading and flowering (middle right); ripening 1 (bottom left); ripening 2 (bottom right).

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11. STUDENT'S STATEMENT

DECLARATION

on authenticity and public access of master's thesis

Student's name: Emmy Goh Ling Ling
Student's Neptun ID: LUJVBS
Title of the document: Effect of Combined Fertilizer and Rice Husk Biochar on Rice Yield, Nitrogen Content, Grain Quality and Water Productivity under Aerobic Rice Cultivation in Hungary
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Name of the consultant's institute: Institute of Environmental Sciences
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12. CONSULTANT'S STATEMENT

STATEMENT ON CONSULTATION PRACTICES

As a supervisor of Emmy Goh Ling Ling (Student's Neptun ID: LUJVBS), I here declare that the master's thesis has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

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