RESPONSES OF PHYSIOLOGICAL TRAITS, GROWTH AND YIELD OF KHAO DAWK MALI 105 AND PATHUM THANI 1 RICE CULTIVARS TO DROUGHT STRESS

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คำสำคัญ : *Oryza sativa*/สภาวะเครียด/สรีรวิทยาของข้าว/ปริมาณโพรลีน/ปริมาณสเปอร์มิดีน/ความชื้นที่จุดวิกฤติ/ความชื้นในดิน

ข้าวเป็นพืชเศรษฐกิจที่สำคัญของประเทศไทยซึ่งเป็นที่ต้องการอย่างมากทั้งในประเทศและต่างประเทศ ข้าวสามารถเพาะปลูกได้ในสภาพแวดล้อมที่หลากหลาย อย่างไรก็ตาม ข้าวเป็นพืชที่ต้องการน้ำปริมาณมาก และค่อนข้างอ่อนไหวต่อสภาวะขาดน้ำเมื่อเปรียบเทียบกับพืชชนิดอื่น การขาดความชื้นในดินและความแปรปรวนของสภาพภูมิอากาศล้วนส่งผลให้ผลผลิตของข้าวลดลงอย่างมีนัยสำคัญ โดยเฉพาะในภาคตะวันออกเฉียงเหนือของประเทศไทย ดังนั้นวัตถุประสงค์ของการทดลองนี้คือ 1) เพื่อศึกษาลักษณะทางสัณฐานวิทยา สรีรวิทยา กระบวนการทางชีวเคมี ผลผลิต และองค์ประกอบผลผลิต ของข้าวพันธุ์ขาวดอกมะลิ 105 (KDML 105) และปทุมธานี 1 (PT 1) ภายใต้สภาวะขาดน้ำ และ 2) เพื่อหาความชื้นจุดวิกฤติของข้าวทั้งสองพันธุ์ โดยใช้การตอบสนองของลักษณะทางสัณฐานวิทยาและสรีรวิทยาในสภาวะขาดน้ำ การทดลองที่ 1 ได้ทำการทดลองเพื่อศึกษาลักษณะทางสัณฐานวิทยา สรีรวิทยา กระบวนการทางชีวเคมี ผลผลิต และองค์ประกอบผลผลิตของข้าวภายใต้สภาวะขาดน้ำในระบบไฮโดรโปนิกส์ โดยปลูกข้าว KDML 105 และ PT 1 ในโรงเรือนภายใต้ 2 สภาพ (ให้น้ำปกติ และสภาวะเครียดจากการขาดน้ำ) แล้วประเมินลักษณะทางสัณฐานวิทยา สรีรวิทยา และกระบวนการทางชีวเคมี ในระยะกล้า ระยะแตกกอ และระยะออกดอก ผลการทดลองพบว่าภายใต้สภาวะขาดน้ำลักษณะทางสัณฐานวิทยาและสรีรวิทยาของข้าวทั้งสองพันธุ์ลดลงอย่างมีนัยสำคัญ ในทุกระยะการเจริญเติบโดยเฉพาะระยะออกดอก โดยลักษณะต่างๆ ของข้าวพันธุ์ PT 1 ลดลงมากกว่าพันธุ์ KDML 105 ซึ่งผลผลิตของพันธุ์ PT 1 ลดลง 36.3–40.9% และพันธุ์ KDML 105 ลดลง 17.9–25.7% และยังพบว่าลักษณะทางสรีรวิทยาของข้าวมีสหสัมพันธ์เป็นเชิงบวกกับผลผลิตทั้งหมด นอกจากนี้ยังพบว่าค่าศักย์น้ำในใบ (LWP) และอัตราการสังเคราะห์แสง มีสหสัมพันธ์เชิงบวกกับผลผลิต การทดลองที่ 2 ดำเนินภายใต้สภาพโรงเรือนเพื่อศึกษาลักษณะทางสัณฐานวิทยาและสรีรวิทยาของข้าวภายใต้สภาวะขาดน้ำ และหาความชื้นจุดวิกฤติของข้าว โดยมีทรีตเมนต์คอมบิเนชั่นคือความชื้นในดินที่แตกต่างกัน 6 ระดับ ที่ 20, 30, 40, 50, 60 และ 70% AWHC ในดินสองชนิด (ดินเหนียว, C และดินร่วนเหนียวปนทราย, SCL) แล้วประเมินลักษณะสัณฐานวิทยาและสรีรวิทยาเมื่อข้าวในระยะกล้า ระยะแตกกอ และระยะออกดอก ผลการทดลองพบว่า ลักษณะทางสัณฐานวิทยา สรีรวิทยา ผลผลิต และองค์ประกอบผลผลิตของข้าวในทุกระยะการเจริญเติบโต

เมื่อขาดน้ำของข้าวลดลงอย่างมีนัยสำคัญ โดยเฉพาะในระยะแตกกอ และระยะออกดอก ส่งผลให้ผลผลิตของข้าวพันธุ์ KDML 105 ลดลงถึง 33–74% และพันธุ์ PT 1 ลดลง 41–74% เมื่อความชื้นในดินทั้งสองชนิดลดลงจาก 70 เป็น 20% AWHC นอกจากนี้ลักษณะทางสรีรวิทยาของข้าว มีค่าสหสัมพันธ์สูงกับน้ำหนักแห้งและผลผลิต แต่ลักษณะ LWP มีค่าสหสัมพันธ์สูงสุดต่อน้ำหนักแห้ง ดังนั้นจึงนำลักษณะนี้มาใช้ในการประเมินความชื้นจุดวิกฤติของข้าวในดินทั้งสองชนิดโดยการวิเคราะห์การถดถอย ผลการทดลองบ่งชี้ว่าความชื้นจุดวิกฤตของข้าวพันธุ์ PT 1 ในดินทั้งสองชนิดที่ระยะกล้าคือ 60% AWHC ขณะที่จุดวิกฤติของพันธุ์ KDML 105 คือ 60 และ 70% AWHC ในดิน C และ SCL ตามลำดับ จุดวิกฤตของข้าวทั้งสองพันธุ์ในระยะแตกกอและระยะออกดอกคือ 70% AWHC ในดินทั้งสองชนิด ภายใต้สภาวะขาดน้ำ ข้าวมีการตอบสนองแตกต่างกันไปตามพันธุ์ และระยะการเจริญเติบโต โดยการทดลองนี้พันธุ์ PT 1 มีความอ่อนไหวต่อสภาวะขาดน้ำมากกว่าพันธุ์ KDML 105 ผลการวิจัยยังบ่งชี้ว่าค่า LWP เป็นลักษณะที่สามารถนำไปใช้ในการศึกษาระดับน้ำในพืชและลักษณะทนแล้ง เนื่องจากมีค่าสหสัมพันธ์เชิงบวกสูงสุดกับผลผลิต และมีผลจากความแปรปรวนของตัวแปรอื่น ๆ ต่ำ รวมทั้งสามารถวัดลักษณะได้ในทุกระยะการเจริญเติบโตโดยไม่ทำลายต้นพืชทั้งหมด นอกจากนี้ค่าความชื้นจุดวิกฤตที่ได้จากงานวิจัยนี้เป็นดัชนีการให้น้ำที่มีประโยชน์ต่อการนำไปใช้ควบคุมการให้น้ำแบบแม่นยำภายใต้ระบบชลประทาน เช่น การจัดการน้ำในนาข้าวด้วยวิธีเปียกสลับแห้ง (AWD) และการปลูกข้าวในระบบประณีต (SRI)

สาขาวิชาเทคโนโลยีการผลิตพืช

ปีการศึกษา 2565

ลายมือชื่อนักศึกษา

ลายมือชื่ออาจารย์ที่ปรึกษา

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม

SARANYAPATH PAIRINTRA : RESPONSES OF PHYSIOLOGICAL TRAITS, GROWTH AND YIELD OF KHAO DAWK MALI 105 AND PATHUM THANI 1 RICE CULTIVARS TO DROUGHT STRESS. THESIS ADVISOR: ASST. PROF. THITIPORN MACHIKOWA, Ph.D. 100 PP.

Keyword : *Oryza sativa*/Drought/Rice physiology/Proline content/Spermidine content /Critical point/Soil moisture content

Rice is an important economic crop in Thailand with high demand for domestic and international trade. Rice can be cultivated in a wide range of environments. However, it is more sensitive to drought compared to other crops due to its high-water requirement. Its yields are significantly affected by soil moisture deficiency and climate variability especially in the Northeastern area of Thailand. The aims of this research were i) to study the morphological and physiological traits, biochemical processes, yield and yield components of Khao Dawk Mali 105 (KDML 105) and Pathum Thani 1 (PT 1) cultivars under drought conditions and ii) to identify the critical soil moisture content (CMC) of rice using the morphological and physiological responses to drought. Experiment 1 was conducted to study the morphological and physiological traits, biochemical processes, yield, and yield components of rice under drought conditions in a hydroponic system. Two rice cultivars, KDML 105 and PT 1, were grown under water stress and non-stress conditions. The morphological, physiological, and biochemical processes were evaluated at the seedling, tillering, and flowering stages. The results showed that the morphological and physiological traits of both rice cultivars significantly decreased under stress at all growth stages particularly at the flowering stage. Under the stress conditions, all traits of PT 1 decreased more than those of KDML 105. Grain yield was reduced by 36.3-40.9% in PT 1 and 17.9-25.7% in KDML 105. Positive correlations were obtained between all physiological traits and grain yield in both cultivars. The highest positive correlations to grain yield were recorded in leaf water potential (LWP) and the net photosynthesis rate. Experiment 2 was conducted under greenhouse conditions to study the morphological and physiological traits of rice under drought and to identify the CMC of rice. Treatment combinations were 6 levels of soil moisture content including 20, 30, 40, 50, 60, and 70% of available water holding capacity (AWHC) and 2 textured soils (clay, C and sandy

clay loam, SCL). All morphological and physiological traits were evaluated at the seedling, tillering, and flowering stages. The results showed that morphological and physiological traits, yield, and yield components of both cultivars significantly decreased under drought stress at all growth stages especially at the tillering and flowering stages. Grain yield was reduced by more than 33-74% in KDML 105 and 41-74% in PT 1 in both soils when soil moisture decreased from 70 to 20% AWHC. All physiological traits positively correlated with dry matter and grain yield in both cultivars. However, LWP had the highest correlations with dry matter. Therefore, it was used to evaluate the CMC of rice in both soils using regression analysis. The results indicated that at the seedling stage, the CMCs of PT 1 were at 60% AWHC in both soils, while CMCs of KDML 105 were at 60 and 70% AWHC in C and SCL soils, respectively. At the tillering and flowering stages, CMCs of both cultivars were at 70% AWHC in both soils.

Under drought, rice response varied between cultivars and growth stages. PT 1 was more sensitive to drought than KDML 105. This research also suggested that LWP could be used for studying plant-water status and evaluate drought tolerant characteristics because it had the highest correlation with grain yield, less influence from other variables, and it can be measured at all growth stages without damaging the whole plant. The CMC values found from this research are very useful watering index which can be applied for precise irrigation control under irrigation systems such as alternate wetting and drying (AWD) and system of rice intensification (SRI).

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CHAPTER I

INTRODUCTION

1.1 Background of problem

Rice (*Oryza sativa* L.) is an important economic crop of the world (Singh et al., 2018). The global annual production was 745.7 million tons which was more than 50% of global cereal production in 2013 (Daryanto et al., 2016). It is an important food crop in Thailand and is a good nutritional source for human health. It has a high demand for domestic and international trade. Its capable to grow in different environmental conditions. However, its yield is often limited by several constraints. Drought is one of the major problems for rice production in many countries that occurs when the soil or plant has a low level of water and continuous loss of water through evapotranspiration (Oladosu et al., 2019). Many previous studies have revealed that rice yields declined in recent years because of drought (Zhang et al., 2018). It has a negative effect on the morphological, physiological, and biochemical processes that related to rice yield and yield components particularly in the reproductive stage (Farooq et al., 2009; El-Sayed et al., 2018; Sahebi et al., 2018).

Drought reduced plant growth by inhibited physiological and biochemical processes that leads to morphological changes resulting in yield and yield components decrease. Under drought condition, low water content leading to reduce cell turgor pressure and water potential, to maintain optimal growth resulting in induce stomatal closure, decrease transpiration rate, and inhibit photosynthesis activities (Wang et al., 2018). Leaf rolling increased to reduce transpiration rate and water loss from rice leaf surface while some morphological traits (dry matter, plant height, tillers number, and root expansion) decreased (Sharifunnessa & Islam, 2017; Cal et al., 2019). Biochemical processes including reactive oxygen species (ROS), polyamines, and proline accumulation increase to reduce oxidative damage and cell death that help to recover more rapidly after stress (Basra, 2000; Wang et al., 2007; Iyer et al., 2013). Finally, yield and yield components were decreased due to drought reduce grain yield, total dry matter, and yield components such as number of tillers, spikelet numbers, panicle number, and filled spikelet (Farooq et al., 2009; Rattanakarn, 2010; Sahebi et al., 2018).The morphological and physiological responses to different watering levels could be used to identify the critical soil water content which is useful for the precision irrigation system. In addition, a particular trait that has a high correlation with grain yield under drought stress could be used to screen drought tolerance in rice breeding programs.

Therefore, the objectives of this experiment were i) to study the morphological traits, physiological characteristics, biochemical processes, yield and yield components of KDML 105 and PT 1 rice cultivars under drought conditions and ii) to identify the critical soil moisture content for rice cultivars (KDML 105 and PT 1) using the morphological and physiological responses to drought.

1.2 Expected results

1.2.1 To obtain the information of rice (*O. sativa* ssp. *indica*) KDML 105 and PT 1 respond to drought stress that could evaluate rice under drought tolerance.

1.2.2 To identify the appropriate watering level and the critical point of soil moisture of KDML 105 and PT 1 cultivars in different soils.

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CHAPTER II

LITERATURE REVIEWS

2.1 Origin and importance of rice

2.1.1 History of rice

Rice (*Oryza sativa* L.) was domesticated from the wild grass around 16,000-14,000 years ago. Archaeologists believed that rice cultivation was started in the Southwest of Nanchang city in Jiangxi, China and the Northern River Plains in the South of India more than 9,000 years ago before propagating to East Asia, Southeast Asia, and South Asia. Historical evidences indicated that rice cultivation in Thailand had longer than 5,500 years ago since Ban Chiang civilization. Rice is an economic crop in Thailand which is the biggest size in the grass family and has a long leaf blade with a leaf sheath covers at node and internode. It has an auricle at the joint of the leaf blade and leaf sheath which is different from other species in this family. It is capable to grow in different weather conditions, high biodiversity, drought-tolerant, and flood-tolerant (Thai Rice Exporters Association, 2020). Normally, its life cycle is around 4-5 months.

2.1.2 Importance of rice

Rice is a staple food for world population. Rice can grow in a wide range of environment which can push global rice stocks to more than a quarter of the rice demand (Farooq et al., 2009). In 2017-2019, worldwide rice production had outpaced consumption by more than 9.0 million metric tons. Rice trade was highly concentrated on the export with five countries including India, Thailand, Vietnam, Pakistan, and the U.S. accounting for 75% of the total world rice exports as shown in Figure 2.1 (Durand-Morat & Bairagi, 2021). However, rice is considered as one of the most drought-susceptible plants when compared to other crops (Oladosu et al., 2019). In recent years, Thailand's rice production is at the lowest level in the decade due to weather conditions and irrigation restrictions. The important factors that affect rice production are 1) internal factors including cultivar or plant genetic and 2) external factors or environmental factors including temperature, light, soil, and water which are important factors that affect the morphological, physiological, and biochemical processes of rice. Prabnakorn et al.

(2018) revealed that rice yields were reduced due to soil moisture deficiency and climate climate variability especially in Northeastern area of Thailand where about 90% of rice cultivation is under rainfed condition. There is high possibility that the yield losses will become more severe in the future due to the increased average daily temperature (Zhao et al., 2017; Prabnakorn et al., 2018; Durand-Morat & Bairagi, 2021).

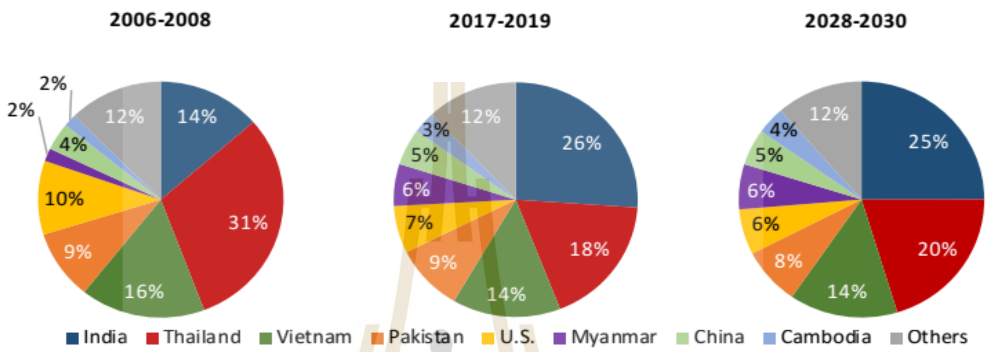

Figure 2.1 Export shared by the top rice exporters (Durand-Morat & Bairagi, 2021).

Drought stress is a serious environmental stress and the major constraint to rice productivity. Drought has an effect at various levels and all stages of the rice life cycle for example induces stomatal closure, reduces gas exchange, and disturb photosynthesis activities. It also has a negative effect on plant height, number of tillers, number of panicles, and dry biomass yield also. Thus, it will be necessary to increase biomass production and economic yield under the climate fluctuation and water availability constrains. The improvement of rice cultivars which have a resistant to drought stress ability is the way to increase the demand for rice production in many countries (Farooq et al., 2009).

2.2 Rice botanical characteristics and rice classification

2.2.1 Rice botanical characteristics

Roots are fibrous system which is approximately 30-40 cm in length and 2-3 mm in diameter. The primary roots appeared in a short period after germination then its was replaced by secondary roots (crown roots or adventitious roots) that produced from underground nodes of young culms (Figure 2.2a).

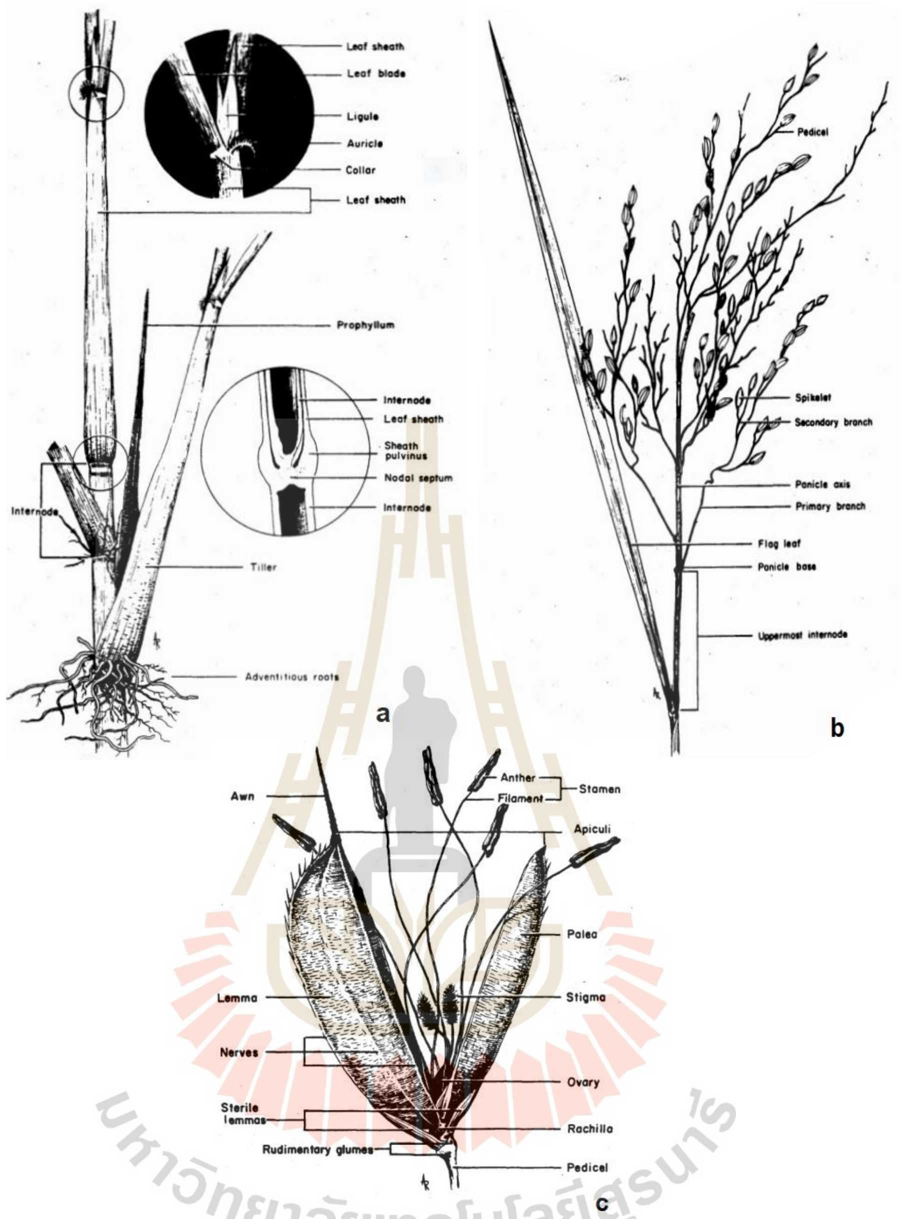

Figure 2.2 Morphology of rice plant. a) tiller structure b) panicle structure and c) spikelet structure (Chang & Bardenas, 1965).

Culms are approximately 35-150 cm tall or depending on the cultivar and growing condition. Culm is the jointed stem of rice that consists with node, internal node, and inter node. The inter node at the base is shorter than inter node above the shoot. A joint-like thickening at the node is called a pulvinus. Rice tillering system includes the main axis and tillers. The crown node is developed to a new tiller from origin plant (Figure 2.2a).

Leaves are developed from the node and had the same characteristics as other species in Poaceae that includes leaf sheath, leaf blade, ligule, and auricle. The first leaf under the spikelet is called flag leaf (Figure 2.2a, b).

Inflorescence and spikelet, the panicle is on the top of the shoot approximately 14-42 cm long. Each spikelet contains 50-500 flowers. Spikelet or flower are developed on the pedicel, that contain three florets and only one floret on the top is developed with two flowering glumes (lemma and palea). One floret has six stamens and one stigma (Figure 2.2b, c) (Chang & Bardenas, 1965).

2.2.2 Rice classification

The two major rice cultivars grown worldwide today are *O. sativa* ssp. *indica* and *O. sativa* ssp. *japonica*. In ecogeographical terms, japonica is mostly found in warm and cold area such as East Asia, upland areas of Southeast Asia, and high elevations in South Asia. Its stickier than indica rice because its moderate elasticity and stickiness due to its low amylose content. It is capable to grow in cold weather but more sensitive to drought, while Indica is more tolerant to drought but its yield per unit area is lower than Japonica. Indica is known as lowland rice that grows well in tropical area in South Asia and Southeast Asia such as India, Sri Lanka, Thailand, Myanmar, and Vietnam. Generally, this subspecies could grow in low soil fertility and tolerate to water stress (Wapet, 1994; Garris et al., 2005; Kang et al., 2006). Thailand is the top five largest rice exporting country in the world which is accounting for 74% of the global rice export in 2006-2008 (Durand-Morat & Bairagi, 2021). Rice is a staple food in Thailand and it has many different types, each type of rice has its own unique properties and naturally gluten-free. The most common types of rice in Thailand are divided into 4 major types by growing areas as following as:

1) Thai Hom Mali Rice, is originated in Thailand with aromatic scent and non-glutinous rice cultivars that is sensitive to photoperiod. For example, Khao Dawk Mali 105 (KDML 105), It has a pandanus-like aroma scent and it has been developed from White Dawk Mali rice that originated in Bang Khla, Chachoengsao, Thailand. Thung Kula Jasmine Rice is Thai Hom Mali Rice comes from the largest flat territory in the Northeast. It has long, slender, and seedy grain. Pathum Thani Rice also has similar characteristics as Hom Mali Rice, but it is a non-photoperiod sensitivity cultivar and cloud be grown in off-season in central areas of Thailand.

2) Glutinous rice (sticky rice) is commonly grown in Northeast areas of Thailand including RD6, Khao Wong Kalasin, Khao Niew Kiew Ngoo, and Black glutinous rice. RD6 is the most popular and high yielding cultivar which is widely grown in the north and northeastern areas. It has unique characteristics of opaque grains, glue-like texture when cooked, very low amylose content, and high amylopectin (Jiang & Raney, 2019).

3) White rice, there are many cultivars of white rice which is commonly grown in Thailand for examples, Kho Leuang Patew Chumphin and Khao Jek Chuey Sao Hai. White rice is grown throughout the country, but the most popular area is the central area of Thailand and could be grown two or three times a year. It has a lot of grain per ear, long grain, and suitable to grow under acid soil.

4) Brown rice or Red rice has a higher fiber 3-7 times than white rice because rice milling machines remove the rice husk while keeping rice germ and rice bran. Riceberry is most well-known brown rice cultivar which is a cross breeding between aromatic black rice and KDML 105. It has sticky texture, fragrant, and can be grown throughout the year (Golden Grain, 2019)

2.2.3 Cultivars and types of rice in Thailand

Rice is consumed within the country by more than 56% and rice exports tend to increase every year. Rice is divided into two groups by photoperiodism (Rice Department, 2016a) including photoperiod sensitivity and non-photoperiod sensitivity rice (Thomas & Vince-Prue, 1996). Photoperiod sensitivity rice such as RD5, RD6, KDML 105, and Nam Sa-gui 19 start flowering when day length is shorter than 12 hours. These cultivars could be grown and yielded only once per year between May-October in Thailand. In contrast, non-photoperiod sensitivity rice cultivars such as RD41, RD49, Chai Nat 1, Suphan Buri 1, Pathum Thani 1 (PT 1), and Phitsanulok 2 flowering date depends on plant age and could be grown and yield all years round. It is mostly cultivated under irrigated area in central region of Thailand (Rice Department, 2016a). However, rice is considered as one of the most drought-susceptible plants compared to other crops. It is necessary to increase rice production and yield under conditions constrained by climate and water availability. Therefore, the most popular Indica rice subspecies including KDML 105 and PT 1 which are widely grown in Thailand and capable to grow under low soil fertility were selected to study drought stress response in this research.

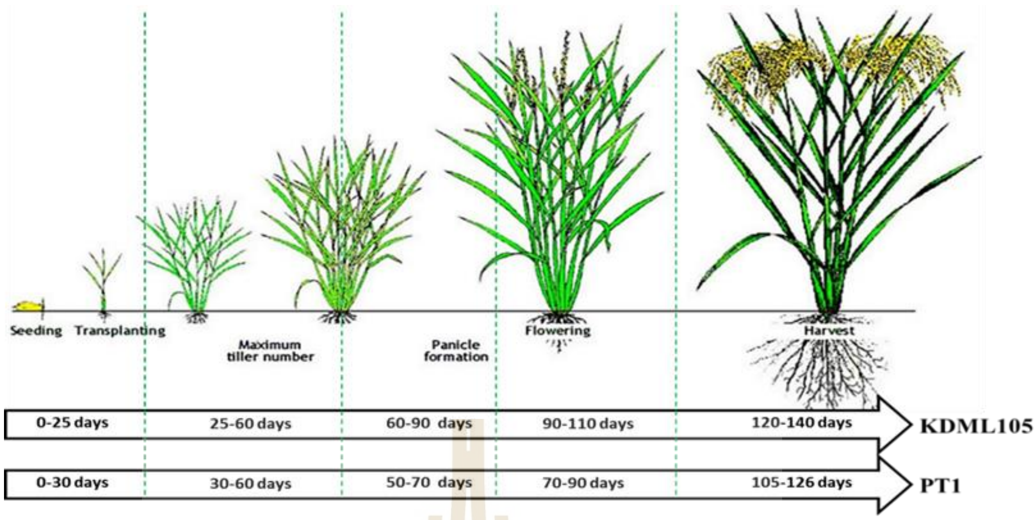

Figure 2.3 The growth stages of rice (KDML 105 and PT 1) adapted from Nelson et al. (2014).

Khao Dawk Mali 105 (KDML 105) is a photoperiod sensitivity cultivar that is defined as the responses of plants to the relative lengths of light and dark periods by flowering when day length shorter than dark period. Thus, the planting season of this cultivar mostly started from August to November. It has a distinctive texture, fragrance, high cooking quality, and high value more than non-aromatic cultivar. KDML 105 rice was the world's best rice for two consecutive years at the 9th The Rice Trader (TRT) World Rice Conference 2017 (Chan-in et al., 2020). This cultivar was produced annually approximately 2.82 tonnes per hectare in Thailand (Rice Department, 2016b). Thai Rice Exporters Association (2021) also reported that KDML 105 was exported to international trade around 711-713 U.S. Dollars per metric ton in April, 2021. It is capable to grow under drought conditions and is mildly tolerant to acid sulfate and saline soil. It well adapts in a rainfed lowland ecosystem by improving its root system plasticity and root branching ability for rapid recovery to capture water in the soil (Vanavichit et al., 2018; Sarutayophat et al., 2020). However, its rice grains are easy to fall off the panicle and it is sensitive to leaf spot, brown leaf spot, ragged stunt disease, and brown planthopper (*Nilaparvata lugens*). The life cycle of KDML 105 cultivar is generally 120-140 days and growth stage are divided into three stages including vegetative or tillering stage at 25-60 days, reproductive stage at 60-110 days, and harvest stage at 120-140 days (Rice Department, 2016b; Chanoknumchai, n.d.).

Pathum Thani 1 (PT 1) is known as the international milled rice trade with high yielding. It is a non-photoperiod sensitivity cultivar and cloud be grown in-season and off-season but is mostly cultivated in-season from May to October. It was first hybridized and selected between BKNA6-18-3-2 and PTT85061-86-3-2-1 lines by Pathum Thani Rice Research Center. PT 1 is similar to KDML 105 in shape, texture, and has a higher resistance to plant diseases and insect more than KDML 105 (Udomkun et al., 2018). It has resistant to leaf spot disease and brown planthopper but sensitive to green rice leafhopper, rice ragged stunt disease, and yellow orange leaf disease. This cultivar was produced annually at approximately 4.84 tonnes per hectare which is higher than the average grain yield in KDML 105 because its cloud be grown year-round and not sensitive to photoperiod (Rice Department, 2016c). Mostly in this cultivar is grown under irrigated areas in the Central region of Thailand with enough water supply rice yield increased more than 20% (Sreethong et al., 2018). PT 1 yield was higher than other cultivar in irrigated areas however, its yield reduced more than KDML 105 under drought stress which is corresponded to Cha-Um et al. (2010) experiment. The life cycle is generally 105-126 days and growth stage are divided into three stages including vegetative or tillering stage at 30-50 days, reproductive stage at 50-90 days, and harvest stage at 105-126 days (Ransog & Inthalaeng, 1998; Rice Department, 2016c).

2.3 Effect of environmental factors on rice growth and productivity

Rice growth and productivity depend on policy management and environmental behavior, when unfavorable condition appears it affects the economic yields and efficiency of agricultural production. Rice production is largely affected by environmental factors due to weather conditions and irrigation restriction have reduced rice yield in recent years. Therefore, it is necessary to understand the impact of environmental factors on rice production (Hossain et al., 2013; Prabnakorn et al., 2018). The important environmental factors are humidity, temperature, light, wind, water, and soil. These factors directly and indirectly affect morphological, physiological, and biochemical processes of rice as described below.

Humidity has a positive and significant effect on all types of rice production and the impact on rice growth is not clear but related to light intensity and temperature. High light intensity and high temperatures result to low humidity while the rainy season and cold temperatures have high humidity (Hossain et al., 2013). Increasing of humidity significantly increased spikelet sterility due to its high pollen sterility and reduced deposition of viable pollen grains on stigma which directly affect rice yield (Weerakoon et al., 2008).

Temperature, the optimal temperature range is between 25-35^{o}C, higher or lower temperature than the optimal may indirectly affect growth and rice yield. Mainly, the response of rice to the temperature stress varies with the temperature level and its duration (Hussain et al., 2019). Sinnarong et al. (2019) estimated the effects of climate change on rice production in Thailand from 1989 to 2009. The results showed that increasing temperature in growing season (between May-October) would lead to reduced rice production by more than 4.56-33.77% and rice production variability increased by 3.87-15.70%. Arunrat and Pumijumnong (2015) also revealed that increased temperature will reduce agricultural productivity and farmers will be necessary to adapt to minimize the adversely effect. Moreover, planting dates should be adjusted to avoid high temperature at reproductive stage because it can induce severe spikelet sterility and delay flowering in some cultivars (Matthews et al., 1997).

Light intensity and light period are necessary for the photosynthetic activity that relate to rice growth and development. Rice requires about 1500 bright sunshine (BSS) hours from the vegetative stage to harvest stage while low light intensity could induce a loss of rice yield and results in poor grain quality. However, it depends on rice subspecies and cultivars (Liu et al., 2014; Barmudoi & Bharali, 2016). Liu et al. (2008) revealed that low light intensity during grain filling affected yield, physiological characteristics, and quality of rice. Mostly, native rice cultivars in Thailand are short-day plants whose flower is accelerated under on short-day condition when the day length is less than critical period (Brambilla & Fornara, 2013). The day-to-flowering of rice cultivars grown in Thailand are varied depending to their photoperiods and critical day length (Khotasena et al., 2022).

Wind direction and wind velocity have a significant influence on rice crops. It could induce the increase of carbon dioxide in the plant canopy for photosynthetic activity while strong wind has the effect of reducing water balance in the leaves (Whitehead, 1965). Wind velocity played a dominant role in the regulation of guttation and strong wind accelerates the drying of the plants by replacing humid air by dry air in the intercellular spaces (Singh et al., 2009). Ishimaru et al. (2012) found that high wind velocity increases the sterility of spikelet induced by heat. Moreover, the dispersal of rice pollen significantly influenced by wind direction, wind speed, and wind advection also have a direct effect on evapotranspiration of non-photoperiod sensitivity cultivar (RD 23 and RD 7) in dry season (between March to May in Thailand) (Mizutani et al., 1989; Song et al., 2004).

Water is one of the important factors that affect rice growth and productivity. Water deficit at the reproductive stage has the most negative effect on rice yield because transpiration activity of this stage is higher than any stage. Water loss from the soil surface is higher at vegetative stage and gradually decreases until harvesting. The water requirement of rice is approximately 6-10 mm per day depending on soil texture and weather conditions (Supasak, 1994). The Food and Agriculture Organization (FAO) also reported rice water consumption is between 450-700 mm during the growing season (Brouwer & Heibloem, 1986). Xiong et al. (2018) also suggested that drought and flood abrupt alternations could decrease rice yield and yield components, and harm some physiology and biochemical processes. Moreover, Fukai, Sittisuang, and Chanphengsay (1998) summarized that lacking of water, severe water stress, cultivars, and soil conditions are the major constraints to rainfed lowland rice production in Thailand. Thus, some farmers tried to cultivate rice in irrigated areas during rainy season for supplementary water supply to reduce the effect of drought prone environments (Arunrat & Pumijumnong, 2015).

Soil is an important factor that is used to decide which water system is suitable for rice production and provides ecological functions including balancing nutrients and water cycles (Dou et al., 2016). Rice is capable to grow in many types of soils but grows well in clay and loamy clay soils due to its high available water holding capacity. 46% of the agricultural area in Thailand was used for rice cultivation and is mostly in the Northeast region. Lacking of irrigation water and low soil water content have been the problems in rice production for many years because rice production in this area is under rainfed system and in coarse textured soils of low water holding capacity (Arunrat et al., 2020). For this reason, rice cultivated in rainy season or irrigated area help to avoid aversely effects from environmental stress.

Considering to above-mentioned facts, it can be concluded that understanding the relationship between plant growth and environmental factors could help farmers to allocate resources more efficiently. While suitable irrigation management also increases rice yield and avoid the negative effect of environmental stress. Soil moisture content and critical soil moisture are important information for irrigation management to maintain optimal growth and yield under conditions constrained by climate and water availability.

2.4 Soil moisture and critical soil moisture content on rice development

Drought and soil problems are the main constraints in rice production as rice suffers from these restrictions often resulted in the reduction of rice yield. In 2013, about 3,850 km^2 of agricultural areas and 9 million people were affected by drought. The damage in 2014 was even greater with 6,800 km^2 and 9 million people affected (Department of Water Resources of Thailand, 2016). Thus, soil moisture or soil water content is crucial for the sustainable improvement of rice production and water management. Soil moisture or soil water content is an expression of the mass or volume of water in the soil (Novák & Hlaváčiková, 2019). It is related to water status in soil and the amount of nutrients available in plants. Too high or too low soil moisture content resulted in decreased seed germination, plant growth, and yield components (Bierhuizen & De Vos, 1959; Tu & Tan, 2003; Lan-Ping et al., 2011; Chadha et al., 2019). The appropriate amount of soil moisture for plant growth and development should be equal or not below the critical soil moisture.

Critical soil moisture content (CMC) is referring to soil water content at the moment of the first reduction in stomatal closure (Jong Van Uer, 1997) or the reduction in plant growth mechanism and yield. The critical point is the point of the first reduction of plant water consumption which resulted in the reduction of plant growth and yield. The critical soil moisture is depending on plant cultivar, growth stage, and soil texture. The differentiation of plant cultivars and plant age results in the different critical soil moisture content because it has a different root elongation and expansion system, each stage of the plant cycle is requiring a different amount of water consumption. Xia et al. (2015) explored the critical soil water effect on physiological parameters (photosynthesis, transpiration, and water use efficiency) in order to determine the water supply level that is necessary to promote physiological traits and enhance water use efficiency.

Soil texture is one of the important factors that affect critical soil moisture and available water holding capacity because each soil texture contains a different level of soil moisture content resulted in the different levels of critical soil moisture and available water holding capacity in each soil texture. Bielorai (1973) and Hsiao (1993) suggested decreasing of dry matter could be used to study the critical point but it takes a long time and data information can be collected only at harvesting or ripening stage of plant while physiological traits such as leaf water potential, net photosynthesis, and stomatal conductance are more sensitive to critical soil moisture content. It can be repletely observed throughout the growing season and not damage the plant samples. However, physiological responses to soil moisture content still did not find the important traits that can be used to determine the critical soil moisture content precisely in rice.

Moreover, Tao et al. (2007) reported that rice grew normally when the soil moisture was maintained at 80-90% of water holding capacity (WHC) when the soil moisture fell to 5-8% below the designated levels, rice growth development was reduced. Zhang, Han, and Du (2007) found that only the lowest water content treatment (below 55%) resulted in the reduction of filled grain number and grain yield of rice. From the previous studies, it can be seen that to maintain optimal growth and yield of rice, irrigation must be applied when the soil moisture reaches critical levels. Therefore, it is important to determine the critical soil moisture contents for specific soils and rice cultivars for precision irrigation control in a certain environment by study the responses of morphological and physiological traits to drought. In the future study, it may be used to arranging irrigation management, monitoring crop drought response, and estimating crop productivity under drought.

2.5 Effects of drought stress on rice growth and yield

Drought stress is an environmental stress which affects the morphological, physiological, and biochemical processes of rice at various levels and every stage of the rice cycle. It refers to the inadequacy of water availability including period without significant rainfall (Oladosu et al., 2019) and occurs when the soil or plant has a low level of water. Many researchers found that grain yield decrease in recent years because of drought.

2.5.1 Effect of drought stress on rice growth

Drought stress causes the reduction in rice growth and yield at various levels throughout the rice growth cycle by affecting morphological and physiological traits that are related to rice yield. Rice is most susceptible to drought at vegetative and reproductive stages. Drought stress at the early stage mostly results in biomass reduction, shoot and root length (Bunnag & Pongthai, 2013; Miftahudin et al., 2020). During the reproductive stage, drought stress led to decreases in rice yield by approximately 18-27% due to delayed flowering slowed elongation of the panicle, and reduction in spikelet fertility (Bernier et al., 2008; Ji et al., 2012). Boonjung and Fukai (1996) also reported that a percent spikelet sterility increment resulted in 40% yield reduction in rice plants when drought occurred during panicle formation.

2.5.2 Rice morphology response under drought stress

The effect of drought stress on rice morphology is mostly a reduction in fresh and dry biomass production especially in the reproductive stage which results to yield reductions, more numbers of unfilled grains, high ratio of dry matters of leaves and stems of rice, and reduced plant height (Sarvestani et al., 2008; Farooq et al., 2009; Zain et al., 2014). Leaf rolling and death of leaves occurs when rice is suffering from drought (Sarma et al., 2016; Sovannarun et al., 2019). It also inhibits root development that reduces root expansion. The effects of drought stress on root development included 1) the reduction of root elongation and 2) the effect of suberization on the water and nutrients uptake (Chutia & Borah, 2012). Okami et al. (2015) reported that Indica lowland cultivars produce many of new tillers, reduced leaf number, and tiller size after early-season drought. However, drought-tolerant Indica cultivar had significant increased root length and diameter of root in stress condition (Anupama et al., 2019).

2.5.3 Rice physiology response under drought stress

The reduction of water content in leaves may cause the reduction of turgor pressure in guard cells and induces stomatal closure. To maintain leaf water content, the plant will close the stomata in order to reduce transpiration activity and leaf osmotic potential that limits the gas exchange and disturbed photosynthesis activity for plant survival (Sarvestani et al., 2008; Maisura et al., 2014; Singh et al., 2018; Anupama et al., 2019). It also affects water use efficiency, intercellular CO_2, relative water content, and membrane stability that used as the parameters to evaluate rice drought tolerance (Cha-Um et al., 2010; Pandey & Shukla, 2015). Shekoofa and Sinclair (2018) reported that Indica rice has a strong induction of aquaporins that play the important roles in controlling water transfer in and out of plant cells under drought. Moreover, relative water content and chlorophyll content were significantly declined under drought (Sovannarun et al., 2019).

2.5.4 Biochemical processes of rice under drought stress

During drought stress, reactive oxygen species (ROS) levels increase dramatically resulting in oxidative damage to proteins, DNA, lipids, and cell death (Iyer et al., 2013). Proline content increased and acts as an osmolyte to reduce a negative effect from drought stress while total protein content decrease (Zain et al., 2014; Sahoo et al., 2019; Sovannarun et al., 2019; Hanif et al., 2021). Thus, the proline content can be used as a marker to screen for drought tolerance trait (Anupama et al., 2019). Moreover, polyamines (PAs) contents such as spermidine (Spd), spermine (Spm), and putrescine (Put) are correlated with leaf water status and photosynthetic capacity can decrease oxidative damage to cellular membranes (Sahebi et al., 2018).

Sequera-Mutiozabal et al. (2017) reported that PAs could be promote the drought tolerance of plants. The increasing of endogenous PAs can relieve the inhibition of grain filling in wheat due to drought. In addition, PAs could be increased the starch content in rice grain by increased the grain weight (Li et al., 2020). Spermidine is a small ubiquitous nitrogenous compound that acts as plant growth regulator and is considered a secondary messenger in signaling pathways. Endogenous production of spermidine is associated with drought stress tolerance in soybean and rice (Nayyar et al., 2005; Yang et al. 2007). Rice plants also respond to drought by accumulating abscisic acid (ABA) in root and leaves to induce the stomatal closure and reduce water loss through transpiration (Basra, 2000; Wang et al., 2007).

2.5.5 Yield and yield components

Drought is the limiting factor of rice production in all agroecological regions around the world. It has a negative effect on the morphological and physiological characteristics related to yield components of rice results in reduced rice yield (El-Sayed et al., 2018). The standard measurement of the amount of rice production per area and referred to how much rice grain are produced is called rice yield. Yield components referred to the structures of the rice plant that directly affect rice yield. The three main components including panicle number, grain weight, and biological yield are directly related to rice yield that are mainly objective of breeding programs (Sarhadi et al., 2015; Mitsuya et al., 2019). During drought stress, rice yield and yield components of rice (panicle number, grain number per panicle, 1000-grain weight, panicle length, and filled grain percentage) were reduced (Leilah & Al-Khateeb, 2005). It has been found to adversely affect panicle initiation and flowering of rice (Sandhu & Kumar, 2017). Yang et al. (2019) reported that drought stress has a high impact on yield components and increases yield loss more than 20%. Moreover, the average estimated economic yield losses of rice higher than 60% due to drought stress in recent years (Kim et al., 2020).

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CHAPTER III

MORPHOLOGICAL, PHYSIOLOGICAL, AND BIOCHEMICAL PROCESSES OF KHAO DAWK MALI 105 AND PATHUM THANI 1 RICE UNDER DROUGHT STRESS

Abstract

This research aimed to study the morphological and physiological traits, biochemical processes, yield, and yield components of rice cultivars under drought conditions. Two rice cultivars, Khao Dawk Mali 105 (KDML 105) and Pathum Thani 1 (PT 1) were grown under two conditions (non-stress and stress) in a hydroponic system. The morphological, physiological, and biochemical processes were evaluated after stress for 7 days at the seedling, tillering, and flowering stages. The results showed that morphological and physiological traits of two rice cultivars were significantly decreased throughout the experiment while biochemical processes (proline and spermidine contents) increased under stress. However, the flowering stage was the most sensitive stage to drought. All traits under the stress of PT 1 decreased more than those of KDML 105 except plant height. Proline content of PT 1 increased more than KDML 105, while spermidine content of KDML 105 was higher than PT 1 under stress. Grain yield reduction ranged from 36.3–40.9% in PT 1 and 17.9–25.7% in KDML 105. Therefore, the magnitudes of response vary to cultivar and growth stage of rice, due to KDML 105 is a rainfed lowland cultivar that is sensitive to photoperiod and grows well in-season while PT 1 is non-photoperiod sensitivity and suitable for the irrigated area. Additionally, all physiological traits had positive correlations with dry matter and grain yield in both cultivars. The highest correlation to grain yield was obtained from leaf water potential (LWP) and net photosynthesis rate. These results indicated that PT 1 was more sensitive to drought than KDML 105 and the flowering stage was the most sensitive stage. In addition, LWP could be used for studying plant-water status and drought tolerant character because it had the highest correlation to yield, less influence from other variables and can be repeatedly measured.

Keywords: Drought, Leaf water potential, *Oryza sativa*, Proline content, Spermidine content

3.1 Introduction

Rice is an important economic crop in the world with increasing demand for international trade and it is a good nutritional source for human health. The growth and physiological response of rice that are sensitive to drought varies with planting season, cultivars, and growth stage. Mostly rice plants are susceptible to drought stress with consequent low-yield potential (Joshi et al., 2011). However, Indica rice (Chai Nat 1 (CNT 1), KDML 105, San-pah-tawng (SPT 1), and RD 6 cultivars) could grow under low soil fertility, tolerance to drought, and widely grown in the tropical zone of South Asia. KDML 105 cultivar has a distinctive texture, fragrance, and is capable to grow under drought conditions and adapt to a rainfed lowland ecosystem by improving its root system and root branching ability (Vanavichit et al., 2018; Sarutayophat et al., 2020). PT 1 is a non-photoperiod sensitive cultivar that has high yield productivity. It could be grown year-round in any environmental conditions but it's commonly grown under irrigated areas and high resistant to many rice diseases and insect pests.

Drought stress is the main constraint to rice productivity at various levels and all stages of rice by affecting growth, physiological characteristics, and some biochemical processes. Generally, it occurs when the soil or plant has a low level of water due to a continuous loss of water through evapotranspiration (Oladosu et al., 2019). During vegetative stages, drought had a small effect on rice development and yield while at reproductive stage, drought reduced rice yield by more than 30% due to the significant reduction of the physiological process (Boonjung & Fukai, 1996; Yang et al., 2019). Under drought conditions at flowering stage, grain yield decreased by more than 50% due to the reduction of fertile panicle and filled grain (Sarvestani et al., 2008). Nowadays, water resources for agriculture are limited and estimated that by 2025, it will be less available, and irrigated rice production will suffer from water scarcity (Lampayan et al., 2015). Drought induces the reduction of rice growth and development which has adverse effect on the morphological and physiological traits related to the yield of the rice. Several experiments were performed to simulate different water stress conditions induced by PEG. The results exhibited that PEG can be used to modify osmotic potential and induced plant water deficit by increasing osmotic potential, which is similar to soil drying and used to simulate drought stress in plants (Zhang et al., 2019). Studies of plant response to drought stress could be used to identify a drought tolerant character for developing rice cultivar that adapted to drought and increased grain yield (Joshi et al., 2011). Several characteristics could be used to evaluate rice drought tolerance for the breeding program such as leaf water content, net photosynthesis, and proline content. These traits are easily observed and can be performed multiple times in large numbers without destroying the whole plant compared to other growth parameters and yield components. The selection for important agronomic traits such as plant height, tiller number, and panicle numbers response to drought can be used to evaluate drought tolerant character that maintains optimal growth with high yield productivity under water scarcity. In addition, improving water use efficiency could help to maintain optimal growth and yield. The improvement of rice plants which has resistant to drought stress is the way to increase rice growth and grain yield in many countries by improving yield components including number of panicles, seed weight, and filled spikelet. Therefore, this experiment aimed to study the responses of morphological and physiological traits, biochemical processes, yield, and yield components of rice cultivars (KDML 105 and PT 1) to drought conditions.

3.2 Materials and methods

3.2.1 Experimental design and plant materials

Two rice cultivars, KDML 105 and PT 1, were used in this study. The experiment was conducted under greenhouse conditions at Suranaree University of Technology, Nakhon Ratchasima, Thailand from January to March 2022. Seeds of KDML 105 and PT 1 cultivars were germinated until true leaf and root were presented. For ten days seedlings were transplanted into the plastic trays (36 cm long x 600 cm wide x 12 cm height) containing Hoagland’s nutrient solution (Hoagland & Arnon, 1950) under a hydroponic system that was continuously aerated with an electric pump. Hoagland’s nutrient solution with a composition of N (220.25 mg/L), P (31.77 mg/L), K (233.26 mg/L), Ca (184.32 mg/L), Mg (38.22 mg/L), S (63.98 mg/L), Fe (3.79 mg/L), Zn (0.05 mg/L), Cu (0.02 mg/L), Mn (0.50 mg/L), B (0.50 mg/L), and Mo (0.01 mg/L) were adjusted every 5 days to maintain the nutrient concentration until harvest stage.

To study the drought stress responses of rice, the experiment was conducted in Completely randomized design (CRD) with 10 replications. Treatments were two water conditions including water-saturated (non-stress) and induced water deficit (drought stress) conditions. In water saturated conditions, the nutrient solution was adjusted every 5 days throughout the growing period. While in induced water deficit conditions, the nutrient solution was adjusted every 5 days until the plants reached seedling stage (10-15 days) then 5% of PEG-6000 was added to create a mild water stress condition (equivalent to -0.5 MPa) (Neumann, 2003). Distilled water was adjusted every 5 days to replenish water lost through evaporation and transpiration. The pH of the nutrient solution was maintained between 5.8-6.5 and the nutrient concentration was maintained at electrical conductivity (EC) of 1.8 dS/m in both treatments throughout the experiment. The morphological, physiological, and biochemical processes of rice were measured at 7 days after inducing drought stress at the seedling, tillering, and flowering stages. Yield and yield components were determined at the physiological maturing stage.

3.2.2 Data collections

After drought stress induction, growth parameters including plant height and dry matter were recorded, at seedling, tillering, and flowering stages of each cultivar. Predawn leaf water potential (LWP_{pd}) was measured by pressure chamber (3005F01 New Plant water Status Console). Photosynthetic parameters including net photosynthesis rate (A) and stomatal conductance (g_s) were measured by portable photosynthesis system (LCi T compact photosynthesis system) at the third leaf counted from the shoot. SPAD chlorophyll reading was recorded by SPAD-502 chlorophyll meter with three-time readings for each replication. Chlorophyll fluorescence (Fv/Fm ratio) was measured by chlorophyll fluorimeter (Handy PEA) (Mishra & Panda, 2017). Proline content (Pro) was determined by Bates et al. (1973) and spermidine content (Spd) was following by Huang et al. (2017) method. Yield and yield components (number of panicles per plant and grain yield per plant) were determined at physiological maturing stage. During the experiment, daily temperature (°C) and relative humidity (%RH) were recorded by WiFi Farm kit sensor (WiFi Sensespeak sensor).

3.2.3 Statistical analysis

Data were analysed using the SPSS software (version 16; SPSS Inc.; Chicago, IL, USA). The differences between treatment means were compared by LSD (Least Significant Difference). Correlation analysis between physiological traits and grain yield of rice was performed.

3.3 Results and discussion

3.3.1 Climatic parameters

During the experiment (January-March, 2022), the daily temperature ranged from 23.71 to 39.65°C and relative humidity ranged from 30.08 to 89.77%.

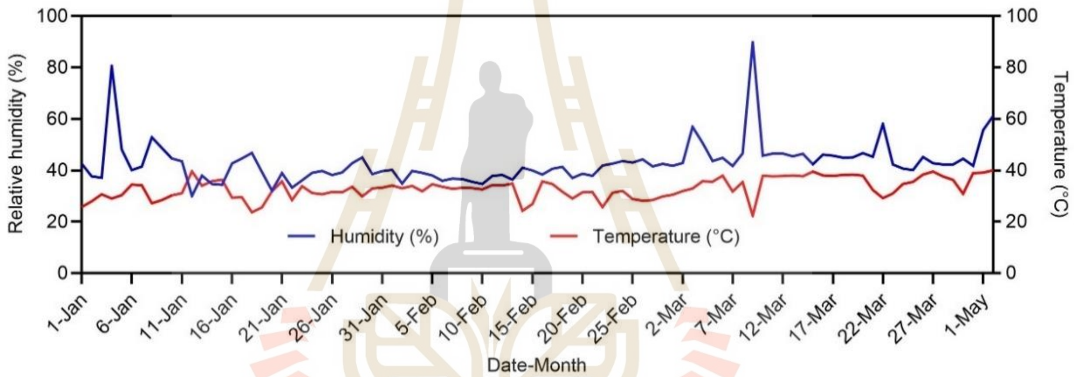

Figure 3.1 Average daily temperature and relative humidity throughout the experiment.

3.3.2 Effects of drought stress on morphological traits

Plant height, the results showed that the plant height of both cultivars decreased under drought stress (Table 3.1). The plant height of PT 1 under stress reduced more than KDML 105 throughout the experiment. Plant height in PT 1 decreased under stress higher than non-stress, especially in tillering and flowering stages (45.50 and 79.87 cm, respectively) while it had no significant difference at seedling stage. Plant height in KDML 105 significantly decreased under stress especially in tillering stage (66.20 cm) while it had no significant difference at seedling and flowering stages (24.27 and 65.07 cm, respectively). Under drought conditions, plant height, root development and leaf area were reduced due to the impaired cell division and elongation (Farooq et al., 2010; Ndjiondjop et al., 2010). It usually occurs when the plant has less water absorption which corresponded with other experiments such as Islam et al. (2018) and Piveta et al. (2020) who reported that seedling height and dry weight decreased in all rice genotypes when water stress levels increased.

Table 3.1 Plant height and dry matter of PT 1 and KDML 105 cultivars' responses to drought stress.

Rice cultivars	Treatments	Plant height (cm)			Dry matter (g/plant)		
		[1]SS	TS	FS	[1]SS	TS	FS
PT 1	Non-stress	24.27	48.90	91.90	6.05	7.98	76.48
	Stress	23.00	45.50	79.87	0.75	5.89	64.38
	Reduction (%)	5.23	6.95	13.09	87.60	26.19	15.82
	Sig	ns	*	**	ns	*	*
	CV%	5.96	2.21	3.43	51.94	3.35	8.87
KDML 105	Non-stress	26.60	70.63	96.00	8.20	10.12	60.21
	Stress	24.27	66.20	65.07	1.38	8.81	44.03
	Reduction (%)	8.76	6.27	32.22	83.17	12.94	26.87
	Sig	ns	*	ns	*	ns	**
	CV%	8.19	2.02	5.76	33.91	3.65	2.68

[1]SS, seedling stage; TS, tillering stage; FS, flowering stage.

*, **, ns significant differences at ≤0.05, 0.01, and non-significant respectively.

Dry matter per plant, the results showed that the dry matter of both cultivars decreased under stress conditions throughout the experiment (Table 3.1). Dry matter in KDML 105 reduced under stress more than in PT 1 throughout the rice cycle except at flowering stage. Dry matter in PT 1 under stress significantly decreased more than non-stress at seedling and tillering stages (0.75 and 5.89 g/plant). Besides, dry matter in KDML 105 significantly decreased under stress from seedling stage to tillering stage (1.38 to 8.81 g/plant), then significantly reduced to 44.03 g/pot at flowering stage. Compared to non-stress, the average dry matter reduction by approximately 43.20% in PT 1 and 40.99% in KDML 105 during the experiment. Drought stress at early period caused the reduction in dry matter and grain yield due to early senescence of leaf, reduced tillers number, low photosynthetic rate, and low leaf area (Kumar et al., 2006). These results were in agreement with the study of drought stress in rice found that dry matter in all rice cultivars reduced by more than 55% after stress for 7 days, particularly in KDML 105 cultivar (Larkunthod et al., 2018). Violita and Azhari (2021) also found that shoot length and dry weight reduced with the increase of PEG-8000 level in all rice varieties in West Sumatera.

3.3.3 Effects of drought stress on physiological characteristics

Predawn leaf water potential (LWP_{pd}), the results showed that LWP_{pd} of both cultivars decreased under stress more than non-stress at all growth stages (Table 3.2). LWP_{pd} in KDML 105 reduced under stress more than PT 1 throughout the rice cycle except at flowering stage. LWP_{pd} in PT 1 under stress significantly reduced more than non-stress from seedling stage to flowering stage from -10.07 to -17.70 bar. LWP_{pd} in KDML 105 under stress significantly reduced throughout the growing period except for tillering stage (14.60 bar). It significantly reduced from -16.58 to -16.57 bar at seedling to flowering stages. LWP is related to water status and available nutrients in plants due to drought effect on water absorption and a limited amount of water that led to reduced turgor pressure and water potential to restricted adversely affected by drought (Reddy, 2019; Reddy et al., 2021). It had been reported that drought significantly reduced morphological and physiological traits in rice particularly LWP (Moonmoon et al., 2020). These results were similar to Salekdeh et al. (2002) research that LWP with well-watered controls was -10.00 bar however, it declined to -24.00 bar after stress for 24 days at tillering stage.

Net photosynthesis rate (A), the results showed that the A of both cultivars decreased under stress (Table 3.2). A in KDML 105 reduced under stress more than in PT 1 at all stages. Under the stress condition, the A in PT 1 significantly reduced compare to non-stress condition at seedling stage and flowering stage from 2.68 and 4.55 μmol/m^2/s. Similar to KDML 105, the A significantly decreased under stress from seedling stage to flowering stage from 2.27 to 3.85 μmol/m^2/s. This result was similar to Zhang et al. (2019) experiment that reported photosynthetic characteristics (net photosynthetic rate, g_s, and transpiration rate) in rice declined when LWP decreased. Punchkhon et al. (2020) research also recorded that all photosynthetic performance including A, g_s, transpiration rate, intercellular CO_2 concentration, ΦPSII, and electron transport rate under drought stress significantly decreased in all rice lines at vegetative stage. Reduction in A is mainly contributed to g_s decreased. Limitation in A is the impaired ATP synthesis, which reduces the synthesis of RuBP and the quantum efficiency of PSII is limited under drought (He et al., 2021).

Table 3.2 Predawn leaf water potential, net photosynthesis rate, and stomatal conductance of PT 1 and KDML 105 cultivars' responses to drought stress.

Rice cultivars	Treatments	LWP_{pd} (bar)			A ($\mu mol/m^2/s$)			g_s ($mol/m^2/s$)		
		[1]SS	TS	FS	[1]SS	TS	FS	[1]SS	TS	FS
PT 1	Non-stress	-5.43	-9.63	-6.00	8.73	13.93	15.62	0.46	0.60	0.71
	Stress	-10.07	-13.57	-17.70	2.68	3.21	4.55	0.16	0.26	0.53
	Reduction (%)	46.08	29.03	66.10	69.30	79.96	70.87	65.22	56.67	25.35
	Sig	**	*	**	**	**	**	**	**	**
	CV%	3.83	10.27	21.86	7.38	17.70	4.09	3.30	19.69	3.91
KDML 105	Non-stress	-9.57	-12.40	-5.00	6.54	12.61	15.45	0.35	0.55	0.71
	Stress	-16.58	-14.60	-16.57	2.27	2.92	3.85	0.14	0.16	0.35
	Reduction (%)	42.28	15.07	69.82	65.29	76.84	75.08	60.00	70.91	50.70
	Sig	*	ns	**	**	**	**	**	**	**
	CV%	17.17	9.49	11.76	3.37	3.88	6.80	4.44	6.50	7.09

[1]SS, seedling stage; TS, tillering stage; FS, flowering stage; LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance.

*, **, ns significant differences at ≤0.05, 0.01, and non-significant respectively.

Stomatal conductance (g_s), the results showed that the g_s of both cultivars decreased under drought stress (Table 3.2). g_s in KDML 105 under stress condition decreased more than PT 1 throughout the experiment. g_s in PT 1 under stress significantly decreased under stress compared with non-stress. It decreased from seedling stage to flowering stage from 0.16 to 0.53 $mol/m^2/s$. Besides, g_s in KDML 105 significantly decreased from seedling stage to flowering stage from 0.14 to 0.35 $mol/m^2/s$ under stress condition. This result was in agreement with Cha-Um et al. (2010) who reported that gs of rice cultivars significantly decreased under mild water deficit. Gujjar et al. (2020) revealed that ABA biosynthesis, signaling proteins, and indorsing stomatal closure were induced under drought stress that might have caused stomata closure and reduced g_s. Under stress conditions, phototropins (Phot1 and Phot2) were disturbed which resulted in stomata closure and low g_s. Dien et al. (2017) reported that drought stress significantly decreased plant growth, root size, and g_s in all rice varieties however, these negative effects depended on rice variety and drought stress period. Yamori et al. (2020) also suggested that enhancing g_s could be improved plant photosynthetic capacities in rice plants.

SPAD chlorophyll reading, the result showed that the SPAD value of both cultivars decreased under drought (Table 3.3). SPAD value in PT 1 under stress decreased more than in KDML 105 during the experiment except for flowering stage. SPAD value in PT 1 had no significant difference at seedling stage (27.83) while significantly reduced to 36.83 and 50.07 at tillering and flowering stages, respectively. Conversely, the SPAD value in KDML 105 significantly reduced to 28.90 at seedling stage while it had no significant difference at tillering stage (38.63) and significantly reduced to 48.33 at flowering stage under stress. In this experiment, SPAD value significantly reduced under stress similar to Mishra et al. (2018) and Chaimala et al. (2021). Drought had negative effect on Fv/Fm and SPAD values due to the PS II activity in rice were disturbed and A decreased (Mishra et al., 2018).

Fv/Fm ratio, the results showed that the Fv/Fm ratio of both cultivars decreased under drought (Table 3.3). Fv/Fm ratio in PT 1 was reduced under stress more than KDML 105 at seedling and flowering stages while KDML 105 was decreased more than PT 1 at tillering stage. Fv/Fm ratio in PT 1 under stress significantly decreased when compared to non-stress from seedling stage to flowering stage from 0.605 to 0.590. Besides, Fv/Fm ratio in KDML 105 significantly reduced from seedling stage to flowering stage from 0.611 to 0.614 under stress.

Drought affected dysfunction and destruction function in the thylakoid structural membrane which is correlated to chlorophyll degeneration that related to leaf senescence and fruit ripening. Under drought condition, photosynthesis activities and chlorophyll content decreased due to early senescence and chlorophyll breakdown (Melkozernov & Blankenship, 2006; Hörtensteiner & Kräutler, 2011; Batool et al., 2022). Yang et al. (2014) also reported that A, chlorophyll content, and chlorophyll fluorescence parameters decreased under severe drought stress. Similar to Nio et al. (2019) research showed that leaf total chlorophyll content decreased due to PEG-induced water stress causing photosynthetic rate and transpiration rate reduction.

Table 3.3 SPAD chlorophyll reading and Fv/Fm ratio of PT 1 and KDML 105 cultivars' responses to drought stress.

Rice cultivars	Treatments	SPAD chlorophyll reading			Fv/Fm ratio		
		[1]SS	TS	FS	[1]SS	TS	FS
PT 1	Non-stress	29.57	39.07	52.70	0.749	0.811	0.737
	Stress	27.83	36.83	50.07	0.605	0.731	0.590
	Reduction (%)	5.88	5.73	4.99	19.23	9.86	19.95
	Sig	ns	*	*	**	**	**
	CV%	8.53	16.73	3.65	4.67	4.10	4.77
KDML 105	Non-stress	30.03	39.70	51.37	0.763	0.791	0.813
	Stress	28.90	38.63	48.33	0.611	0.592	0.614
	Reduction (%)	3.76	2.70	5.92	19.92	25.16	24.48
	Sig	*	ns	*	**	**	**
	CV%	1.54	3.19	1.86	4.60	9.15	4.43

[1]SS, seedling stage; TS, tillering stage; FS, flowering stage.

*, **, ns significant differences at ≤0.05, 0.01, and non-significant respectively.

3.3.4 Effects of drought stress on biochemical processes

Proline content, the results showed that the proline content of both cultivars increased under stress more than in non-stress conditions (Table 3.4). Proline content in PT 1 increased under stress more than KDML 105 at tillering and flowering stages. Proline content of PT 1 under stress significantly increased from seedling and flowering stages (26.10 and 47.81 µg/g FW). Corresponding to KDML 105, proline content under stress significantly increased from seedling stage to flowering stage from 24.82 to 40.28 µg/g FW. Generally, under drought stress, plants accumulate a high proline content to maintain plant water status and turgor pressure by promoting the uptake of K^+, Ca^{2+}, P and N. It helps to reduce the negative effect on membrane organelles, proteins, and enzymes due to drought (Hayat et al., 2012). This result was similar to Pamuta et al. (2022) experiment, that leaf proline contents in all rice lines/cultivars significantly increased and proline concentration was tightly associated with rice growth. Aurabi et al. (2012) also reported that fresh weight and dry weight decreased while proline content increased with increasing PEG concentration in rice tissues.

Table 3.4 Proline content and spermidine content of PT 1 and KDML 105 cultivars' responses to drought stress.

Rice cultivars	Treatments	Proline content (µg/g FW)			Spermidine content (nmol/g FW)		
		[1]SS	TS	FS	[1]SS	TS	FS
PT 1	Non-stress	11.93	10.26	17.84	176.41	219.37	603.22
	Stress	26.10	30.32	47.81	1,593.62	1,810.52	2,498.07
	Sig	**	**	**	**	**	**
	CV%	23.52	7.01	19.95	8.39	8.66	15.51
KDML 105	Non-stress	10.90	13.02	19.16	224.42	287.22	589.34
	Stress	24.82	28.11	40.28	1,453.65	2,187.53	2,755.51
	Sig	**	**	**	**	**	**
	CV%	4.68	19.16	3.89	9.34	8.67	3.86

[1]SS, seedling stage; TS, tillering stage; FS, flowering stage.

** significant differences at ≤0.01.

Spermidine content, the results showed that the spermidine content of both cultivars increased under drought stress more than under non-stress (Table 3.4). Spermidine content in KDML 105 increased under stress more than PT 1 at flowering stages. While spermidine content in PT 1 increased more than KDML 105 at seedling and tillering stages. Spermidine content in PT 1 under stress significantly increased from seedling stage to tillering stage from 1,593.62 to 1,810.52 nmol/g FW and dramatically increased to 2,498.07 nmol/g FW at flowering stage. Besides, spermidine content in KDML 105 significantly increased from seedling stage to tillering stage from 1,453.65 to 2,187.53 nmol/g FW and dramatically increased to 2,755.51 nmol/g FW at flowering stage under stress condition.

These results were in agreement with Yang et al. (2007) who found that spermidine synthase significantly increased by water-stressed. Similar to Zhang et al. (2017) experiment reported free spermidine content increased while sterile spikelet decreased in rice young panicle under drought because spermidine had associated with the inhibiting of drought effect on grain filling which promoted cytokinin and starch synthesis in grains (Li et al., 2020). Normally, spermidine act as free radical scavengers that protect the membranes from oxidative damage and stabilize cell membranes. It also optimizes stomatal opening and closing to reduce the water loss in plant (Farooq et al., 2009; Hasan et al., 2021). Furthermore, many researchers reported that spermidine increased relative water content, chlorophyll contents, photosynthesis rate, and antioxidant enzyme activities while decreasing malondialdehyde, total soluble sugar, and abscisic acid under drought stress (Chen et al., 2017; Xu et al., 2022).

3.3.5 Effects of drought stress on yield and yield components

Number of panicles per plant of both cultivars under drought stress was lower than non-stress (Table 3.5). Number of panicles in PT 1 decreased under stress more than KDML 105 at tillering stage while KDML 105 reduced more than PT 1 at seedling and flowering stages. Number of panicles of PT 1 under stress decreased from seedling to flowering stages from 11.00 to 13.00 panicles/plant. Besides, KDML 105 decreased from seedling to flowering stages from 8.33 to 9.67 panicles/plant.

Table 3.5 Number of panicles and grain yield per plant of PT 1 and KDML 105 cultivars' responses to drought stress.

Rice cultivars	Treatments	Number of panicles per plant (panicles/plant)			Grain yield (g/plant)		
		[1]SS	TS	FS	[1]SS	TS	FS
PT 1	Non-stress	11.33	16.67	16.67	15.42	19.67	19.67
	Stress	11.00	9.67	13.00	9.82	12.61	11.61
	Reduction (%)	2.91	41.99	22.02	36.32	35.89	40.98
	Sig	ns	*	*	*	**	**
	CV%	9.67	21.26	21.26	6.02	5.35	5.64
KDML 105	Non-stress	9.67	12.67	13.00	11.31	13.47	14.47
	Stress	8.33	11.00	9.67	9.28	10.00	10.96
	Reduction (%)	13.86	13.18	25.62	17.95	25.76	24.26
	Sig	ns	ns	ns	ns	*	*
	CV%	12.83	6.90	15.07	11.17	3.81	3.94

[1]SS, seedling stage; TS, tillering stage; FS, flowering stage.

*, **, ns significant differences at ≤0.05, 0.01, and non-significant respectively.

Grain yield per plant, the results showed that both cultivars under drought stress conditions were lower than non-stress (Table 3.5). Grain yield of PT 1 decreased under stress more than KDML 105 at all drought periods. PT 1 under stress significantly decreased from seedling to flowering stages from 9.82 to 11.61 g/plant. Besides, KDML 105 decreased from seedling to flowering stages from 9.28 to 10.96 g/plant.

From the results, drought stress significantly decreased the physiological and biochemical processes of the rice plant which led to morphological, physiological, and biochemical processes changes that resulted in rice growth, yield, and yield components decreased. Yield and yield components of two rice cultivars were decreased under stress particularly in grain yield by more than 36.3-40.9% in PT 1 and 17.9-25.7% in KDML 105. Reduction in grain yield under drought mostly resulted from a reduction in grain weight, number of panicles, and fertile panicles, these traits are important yield components and have a direct effect on rice yield (Sabetfar et al., 2013; Sarhadi et al., 2015; Mitsuya et al., 2019). Grain yield was reduced by more than 40% especially PT 1 due to panicle formation being disturbed by drought during reproductive and ripening stages. However, all traits of two rice cultivars were different in each growth stage and water condition.

KDML 105 cultivar is capable to grow under drought and is well adapted to the rainfed system while rice grains are easy to fall off the panicle. The planting season is mostly started between August to November in Thailand because it is a photoperiod sensitivity cultivar and its mostly flower in shorts day. However, this experiment was conducted between January to March 2021 which is off-season for KDML 105 rice cultivation due to limitations in the growing period, experiment period, and equipment resources. Thus, KDML 105 were grown in the off-season that resulted in delayed flowering, increased incomplete grain filling and yield reduction (Rice Department, 2016a; Vanavichit et al., 2018; Sarutayophat et al., 2020).

On the contrary, PT 1 cultivar is a non-photoperiod sensitivity that was hybridized and selected between BKNA6-18-3-2 and PTT85061-86-3-2-1 lines with gamma irradiation (Rice Department, 2016b). It could be grown year-round under several environmental conditions, particularly in irrigated areas (Sreethong et al., 2018). Anugoolprasert (2016) recorded that PT 1 has a high number of panicles and yields under low water supply while root dry weight while seed weight was less than KDML 105 in the same condition. Therefore, it can be concluded that planting area, environmental conditions, and water application directly effects rice yield because low water supply could decrease grain yield in PT 1 more than in KDML 105.

3.3.6 Correlation analysis between physiological responses and grain yield of rice

Correlation coefficients between physiological characteristics and grain yield of PT 1 cultivar were described in Table 3.5. Highly positive correlations were obtained between grain yield and LWP_{pd} (r = 0.948**), g_s (r = 0.977**), A (r = 0.996**), SPAD value (r = 0.936**), and Fv/Fm ratio (r = 0.979**). A had the highest positive correlations with grain yield (r = 0.996**). Similarly, all traits of KDML 105 had positive correlations between grain yield and LWP_{pd} (r = 0.956**), g_s (r = 0.951**), A (r = 0.957*), SPAD value (r = 0.856*), and Fv/Fm ratio (r = 0.941**) as shown in Table 3.5. A and LWP_{pd}, had the highest positive correlations with grain yield (r = 0.957** and 0.956**, respectively).

Table 3.6 Correlation coefficients of physiological traits and grain yield of PT 1 and KDML 105 cultivars (stress at flowering stage).

Rice cultivars	Traits[1]	g_s	LWP_{pd}	SPAD	Fv/Fm ratio	GY
PT 1	A	0.974**	0.926**	0.906*	0.967**	0.996**
	g_s		0.907*	0.940**	0.964**	0.977**
	LWP_{pd}			0.923**	0.976**	0.948**
	SPAD				0.925**	0.936**
	Fv/Fm ratio					0.979**
KDML 105	A	0.987**	0.985**	0.897*	0.969**	0.957**
	g_s		0.999**	0.940**	0.990**	0.951**
	LWP_{pd}			0.937*	0.994**	0.956**
	SPAD				0.915*	0.856*
	Fv/Fm ratio					0.941**

[1]A, net photosynthesis rate; g_s, stomatal conductance; LWP_{pd}, predawn leaf water potential; GY, grain yield.

*, ** significant differences at ≤0.05 and 0.01 respectively.

The study of the association between physiological traits and yield by correlation correlation coefficient analysis and path coefficient is one of the methods used to obtain information on drought tolerance traits. In this study, correlation coefficients between physiological traits and grain yield of PT 1 and KDML 105 indicated that positive correlations were obtained between grain yield and all physiological traits, particularly in LWP_{pd} and photosynthetic activities. LWP_{pd} and A had the highest and positively significant correlations with grain yield in both cultivars. Yang et al. (2019) experiment reported that grain yield had positively correlated with net photosynthetic rate and g_s under stress and it had a strong influence on rice yield at flowering stage. Corresponded to Bernier et al. (2008) reported a highly positive correlation appeared between LWP_{pd} and grain yield at flowering stage under drought. Jongdee et al. (2002) also suggested that maintaining high LWP helps to minimize the negative effects of water deficit on spikelet sterility and grain yield. Therefore, LWP_{pd} and A are the most important trait for study in plant-water status and drought tolerant genotypes. In addition, these physiological traits could be used to evaluate drought stress levels in rice breeding program which has less influence due to drought period and stress levels.

3.4 Conclusion

Droughts had negative effects on water absorption and the limited amount of water has led to reduced physiological processes such as LWP, turgor pressure, and cell inhibition increased resulting in decreased plant height and dry matter. Conversely, biochemical processes included proline and spermidine contents increased under stress. Grain yield of two rice cultivars decreased under stress by more than 36.3-40.9% in PT 1 and 17.9-25.7% in KDML 105 especially under stress at flowering stage. In addition, positive correlations were obtained between grain yield and all physiological traits, particularly in LWP_{pd}. Thus, LWP_{pd} is a physiological trait that is commonly used to study drought tolerant cultivars and evaluating drought tolerant characters in rice because LWP_{pd} could be indicating the whole plant status and had less influence from other variables. Moreover, the response of physiological traits under drought could be repeatedly observed throughout the rice growth cycle and can be performed multiple times in large numbers.

3.5 References

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CHAPTER IV

RESPONSES OF KHAO DAWK MALI 105 AND PATHUM THANI 1 RICE TO DIFFERENT WATERING LEVELS

Abstract

This research aimed to study the morphological and physiological processes of two rice cultivars (Khao Dawk Mali 105, KDML 105 and Pathum Thani 1, PT 1) under drought stress and to identify the critical soil moisture content (CMC) using the physiological response to drought. Rice cultivars KDML 105 and PT 1 were grown under six levels of soil moisture (20, 30, 40, 50, 60, and 70% AWHC) in two textured soils (clay, C and sandy clay loam, SCL). The morphological and physiological processes were evaluated at seedling, tillering, and flowering stages. The results showed that when the soil moisture levels decreased, morphological and physiological traits of both cultivars significantly decreased at all growth stages, while leaf rolling score increased, in both soils. Yield and yield components also decreased when soil moisture levels decreased. Grain weight was the most sensitive trait, its reduced by more than 33-74% in KDML 105 and 41-74% in PT 1 in both soils when soil moisture decreased from 70 to 20% AWHC. All physiological traits positively correlated with dry matter and grain yield in both cultivars and soils particularly in LWP_{pd} was the most consistent correlating with dry matter and grain yield. Therefore, it was used to evaluate the CMC of rice which was determined from the intersection of two linear regression lines from the correlation between LWP_{pd} and soil moisture content. From the evaluation, at seedling stage, the CMCs of PT 1 were at 60% AWHC in both soils, while CMCs of KDML 105 were at 60 and 70% AWHC in C and SCL soils, respectively. At tillering and flowering stages, CMCs of both cultivars were at 70% AWHC in both soils. These results indicated that the CMC values are the important information which can be applied with irrigation systems such as alternate wetting and drying (AWD) and system of rice intensification (SRI) for reduce water use and determine the watering level more accurately in each soil textures and rice cultivar.

Keywords: *Oryza sativa*, Drought, Physiological characteristic, Critical point, Soil moisture content

4.1 Introduction

Rice (*Oryza sativa* L.) is an important economic crop with high demand for domestic and international trade (Singh et al., 2018). It is an important food crop in Thailand and is a good nutritional source for human health. Indica rice subspecies could grow in low soil fertility, moderately tolerant to drought, and widely grown in the tropical zone in South Asia such as India, Sri Lanka, Thailand, Myanmar, and Vietnam (Wapet, 1994). In Thailand, KDML 105 is the most popular rice cultivar that has a distinctive texture, fragrance, and capable to grow under drought conditions. It can adapt to a rainfed lowland ecosystem by improving its root system and root branching ability (Vanavichit et al., 2018; Sarutayophat et al., 2020). Besides, PT 1 is a popular non-photoperiod sensitive cultivar with high yielding. It could be grown year-round in several conditions but its commonly grown under irrigated areas in Central and Northeastern regions of Thailand. It is highly resistant to major rice diseases and insect pests as well (Udomkun et al., 2018).

Nevertheless, climate change and severe water shortages have threatened rice production in many countries due to population growth and total food consumption increases. Climate fluctuation mainly characterized by increased temperature, shifted rainfall patterns, extreme environmental stress, and have influenced plant water consumption especially in water-intensive crop such as rice, sugarcane, and cotton (Narayanamoorthy, 2005; Jansing, et al., 2020; Muzammil et al., 2020; Luo et al., 2022). Furthermore, it will continue to harm rice yield and grain quality. There is high possibility that the yield losses will become more severe in the future. Thus, efficient utilization of water use is one of the most important practices for sustainable rice production under climate fluctuation, increasing of global food demand and water shortages (Jansing et al., 2020; Luo et al., 2022).

Generally, rice plant is a sensitive to drought due to its small root system, thin cuticular wax, swift stomatal closure, and high-water requirement (Sahebi et al., 2018; Luo et al., 2022). Drought stress is an environmental stress and one of the major constraints for rice production. Many researchers have revealed that rice yields declined in recent years because of drought. It has a negative effect on the morphological and physiological processes that related to yield and yield components at various levels and the whole rice life cycle (Farooq et al., 2009; El-Sayed et al., 2018; Zhang et al., 2018). Prabnakorn et al., (2018) found that rice yield decreased due to soil moisture deficiency and climate variability especially in Northeastern area of Thailand where about 90% of rice cultivation is under rainfed conditions. Therefore, the improvement of water use efficiency is necessary to maintain optimal rice growth and yield under drought in rainfed area. The watering level will depend on plant consumption by maintaining soil moisture at critical level because low soil moisture results in plant growth and yield reduction (Tu & Tan, 2003; Lan-Ping et al., 2011; Chadha et al., 2019).

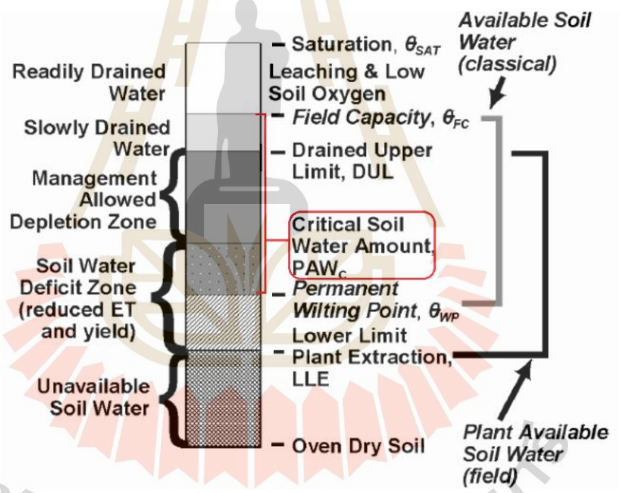


Figure 4.1 Soil water reservoir concepts adapted from Howell and Moron (2007).

Critical soil moisture content (CMC) is soil moisture content at the moment of the first reduction in stomatal closure and plant water consumption (Jong Van Uer, 1997). It is the soil moisture level between field capacity (FC) and permanent wilting point (PWP) (Figure 4.1). The plants should be re-watering when the soil moisture content reach the critical level to avoid adverse impact from water stress. CMC values are important information that could be used to evaluate watering index for precision irrigation management with low production costs and improve rice drought-tolerant in breeding program. CMC should be determined accurately with specific soil textures and cultivars in a certain environment since it is very important for a precision irrigation control (Howell & Moron, 2007; Machikowa et al., 2020). Morphological and physiological traits could be used to determine the CMC. The predawn leaf water potential (LWP_{pd}) was used to determine the CMC in cassava and photosynthetic parameters including photosynthetic rate, stomatal conductance, and transpiration rate were used in tomato, sugarcane, and soybean (Hufstetler et al., 2007; Halperin et al., 2017; Dinh et al., 2019; Machikowa et al., 2020). Considering the above facts, this experiment aimed to study the morphological and physiological processes of rice (*O. sativa* ssp. *indica*) under drought stress in two rice cultivars (KDML 105 and PT 1) and to determine the CMC using the physiological response to drought.

4.2 Materials and methods

4.2.1 Experimental design and plant materials

This experiment was conducted from May to September 2021 under greenhouse condition at Suranaree University of Technology, Nakhon Ratchasima, Thailand. Two rice cultivars, KDML 105 and PT 1, were used in this study. The experimental design was 6x2 factorial in Randomized completely block design (RCBD) with 10 replications. Treatment combinations were six levels of soil moisture content (20, 30, 40, 50, 60, and 70% AWHC) and two textured soils (sandy clay and clay) which were the representative soils for rice cultivation in Northeast and Central parts of Thailand.

4.2.2 Soil analysis and determination watering levels

Soil properties including organic matter (OM) was analyzed following by Sims and Hoby (1971) method, the average of pH and electrical conductivity (EC) were recorded by pH and EC meter (WTW Series inoLab pH/Cond), available P was determined by Bray and Kurtz (1945) method and exchangeable K, Ca, and Mg were analyzed according to Rayment and Higginson (1992) method. Soil textures or soil particle size analysis were determined by hydrometer method (Gavlak et al., 1994).

Available water holding capacity (AWHC) which is the amount of water that held by the soil between FC and PWP was analyzed using pressure plate apparatus (Glorioso

& Ella, 2015; Blaschek et al., 2019). The soil samples were subjected to -0.3 bar and -15.0 bar of suction pressure. After that, the soil samples were oven dried at 105°C for 72 hours. The moisture contents that correspond to the FC and PWP were determined from the mass difference of wet and dry soils (Equation 1 and 2). Then, the AWHC was calculated from the difference between FC and PWP (Equation 3). After that, the watering levels in each treatment were determined.

$$FC = (W_{FC} - W_{DRY}) / W_{FC} \times 100 \quad \text{(Equation 1)}$$

$$PWP = (W_{PWP} - W_{DRY}) / W_{PWP} \times 100 \quad \text{(Equation 2)}$$

$$AWHC = FC - PWP \quad \text{(Equation 3)}$$

where W_{FC} is mass of FC soil, W_{PWP} is mass of PWP soil, and W_{DRY} is dry mass of FC or PWP.

KDML 105 and PT 1 cultivars were grown in the 12 inches pots filled with the soils. Water was applied to saturated soil moisture content in all treatments until 15 days after sowing. Each treatment was adjusted the amount of soil moisture level at 20 to 70% AWHC by a soil moisture meter (Theta Probe with HH2 Soil Moisture Meter) at seedling, tillering, and flowering stages for 5-7 days. Then, the morphological and physiological traits were measured when the soil moisture content in each treatment reached to the designed levels (Table 4.2) at all growth stages. After that, the soil moisture contents were allowed to be reduced to the level of each treatment before re-watering back to the FC. Yield and yield components including number of tillers, number of panicles, 100-grain weight, and grain yield were collected at physiological maturing stage.

4.2.3 Determination of critical soil moisture content (CMC)

Physiological trait that had the highest correlation to dry matter was used to evaluate the CMC at seedling, tillering, and flowering stages. In this study, it was found that LWP_{pd} had the highest correlation to DM and GY, therefore it was used to evaluate the CMC. To determine the CMC of each rice cultivar, two sectional linear regressions between soil moisture content and LWP_{pd} were performed in each soil. In the first linear regression period (low slope), LWP_{pd} gradually decreased with the decreased soil moisture which indicated that plant water absorption was normal. In the second linear regression period (high slope), the LWP_{pd} rapidly decreased that referred to low water absorption due to too low soil moisture content. Therefore, in each soil texture, the

CMC was determined as the intersection of two regression lines (Samongdee, 2016; Thong-Ob, 2017).

4.2.4 Data collections were collected at 7 days after soil moisture content adjustment at seedling, tillering, and flowering stages which depended on soil textures and rice cultivars. KDML 105 cultivar, data were collected at seedling stage (25-35 days days), tillering stage (65-75 days), flowering stage (85-95 days), and harvest stage (115-125 days). PT 1 cultivar, data were collected at seedling stage (25-35 days), tillering stage (55-65 days), flowering stage (80-90 days), and harvest stage (110-115 days).

- Climatic parameters including the average temperature and relative humidity were recorded daily inside the greenhouse during the experiment by WiFi Farm kit sensor (WiFi Sensespeak sensor).

- Morphological traits

Plant height was measured from ground to the tip of the highest leaves of three pots per treatment at all growth stages.

Leaf rolling score was measured from the flag leaves followed Verma et al. (2020) classification which was described in Figure 4.2. The data was collected from three fully expanded leaves per treatment.

0 - Open leaf	3 - U-shaped
1 - Shallow V-shaped	4 - O-shaped
2 - Deep V-shaped	5 - Tightly rolled

Figure 4.2 Leaf rolling classification score (Verma et al., 2020).

- Physiological characteristics

Predawn leaf water potential (LWP_{pd}) was measured from three fully expanded leaves per treatment using a pressure chamber (3005F01 New Plant water Status Console) at 5.00-6.30 AM.

Photosynthetic parameters including net photosynthesis rate (A) and stomatal conductance (g_s) were measured using a portable photosynthesis system (LCi T compact photosynthesis system). Data were determined from three fully expanded leaves (at the third leaf counted from shoot) per treatment in natural fluctuating light at 9.00-10.00 AM with three-time readings for each replication.

SPAD chlorophyll reading was also recorded from three fully expanded leaves (at the third leaf counted from shoot) per treatment by placing the leaf under the sensor and recorded the value. Data were collected from three plant samples per treatment using a SPAD-502 chlorophyll meter with three-time readings for each replication.

Chlorophyll fluorescence was measured as the maximum photochemical quantum yield of photosystem II (Fv/Fm ratio) at midday from three fully expanded leaves (at the third leaf counted from shoot) per treatment using chlorophyll fluorimeter (Handy PEA) (Mishra & Panda, 2017). The leaves were measured after they were incubated in darkness for 15 minutes.

- **Yield and yield components** were collected at seedling, tillering, flowering, and ripening stages which depended on soil textures and rice cultivars.

Dry matter per pot (DM) was collected from three pots per treatment. Plant samples were dried at 70^{o}C for 48 hours by hot air oven after that the dry matter was measured.

Number of tillers per pot was collected from three pots per treatment.

Number of panicles per pot was collected from three pots per treatment.

100-grain weight and *grain yield per pot (GY)* were collected from three pots per treatment at ripening stage.

4.2.5 Statistical analysis

Data were analyzed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA). The differences between treatment means were compared by Duncan's multiple range (DMRT) test. Correlation analysis between physiological traits and DM were performed. Physiological trait that had highest correlation to DM were used to evaluate the CMC at seedling, tillering, and flowering stages.

4.3 Results and discussion

4.3.1 Soil properties and determination watering levels

Analysis result of two experimental soils (the representative soils for rice cultivation in the Central and Northeastern regions) is shown in Table 4.1. The particle size analysis determined by hydrometer method showed that, soil sample #1 contained 34.40, 10.72, and 54.88% of sand, silt, and clay particles and was classified as clay (C), while soil sample #2 contained 60.40, 14.72, and 24.88%, of sand, silt, and clay particles and was classified as sandy clay loam (SCL). The average pH values of both soils were neutral, while EC values were 128.45 and 90.95 µS/cm in C and SCL soils, respectively. Overall soil fertility including available P, Exchangeable K, Exchangeable Ca, and Exchangeable Mg was moderately high in both soils as described in Table 4.1. Organic matter (OM) was moderately high (2.9% OM) in C soil and low (1.3% OM) in SCL soil (Table 4.1).

Table 4.1 Soil properties of two textured soils.

Soil sample	Practical size distribution, %			Soil texture	Field capacity (% vol)	Permanent wilting point (% vol)	Available water holding capacity (% vol)
	Sand	Slit	Clay				
#1	34.40	10.72	54.88	Clay	35.36	18.86	16.50
#2	60.40	14.72	24.88	Sandy clay loam	17.92	10.65	7.27

Soil sample	pH	Electrical Conductivity (µS/cm)	Organic Matter (%)	Available P (ppm.)	Exchangeable K (ppm.)	Exchangeable Ca (ppm.)	Exchangeable Mg (ppm.)
#1	7.7	128.45	2.9	18.86	345.0	3,826.5	35.4
#2	7.3	90.95	1.3	10.65	131.8	2,357.0	17.9

Table 4.2 Levels of soil moisture content of two textured soils.

Soil moisture content (% AWHC)	Clay (C) (% vol)	Sandy clay loam (SCL) (% vol)
70	30.41	15.74
60	28.76	15.01
50	27.11	14.29
40	25.46	13.56
30	23.81	12.83
20	22.16	12.10

From the AWHC analysis, the results showed that in clay soil, the FC and PWP were 35.36 and 18.86% vol, respectively while in SCL soil they were 17.92 and 10.65% vol, respectively. Soil AWHC values were higher in C than in SCL soil i.e. the AWHC in C and SCL soils were 16.50 and 7.27% vol respectively which is corresponded with O'geen (2013) and Easton (2021) soil water relationship concepts. The actual soil moisture content levels of two textured soils were measured from each soil AWHC to determine the watering levels in each treatment (Table 4.2). The actual values were 22.16, 23.81, 25.46, 27.11, 28.76, and 30.40% vol at 20, 30, 40, 50, 60, and 70% AWHC respectively in C soil, while in SCL soil were 12.10, 12.83, 13.56, 14.29, 15.01, and 15.74% vol at 20, 30, 40, 50, 60, and 70% AWHC respectively.

4.3.2 Climatic parameters

During the experiment (May-September, 2021), the daily temperature ranged from 25.38 to 40.01°C and relative humidity ranged from 40.34 to 88.28%.

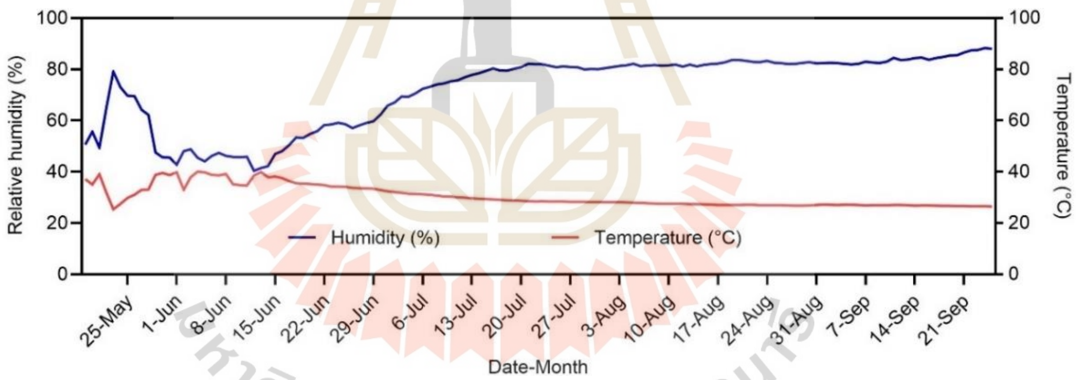
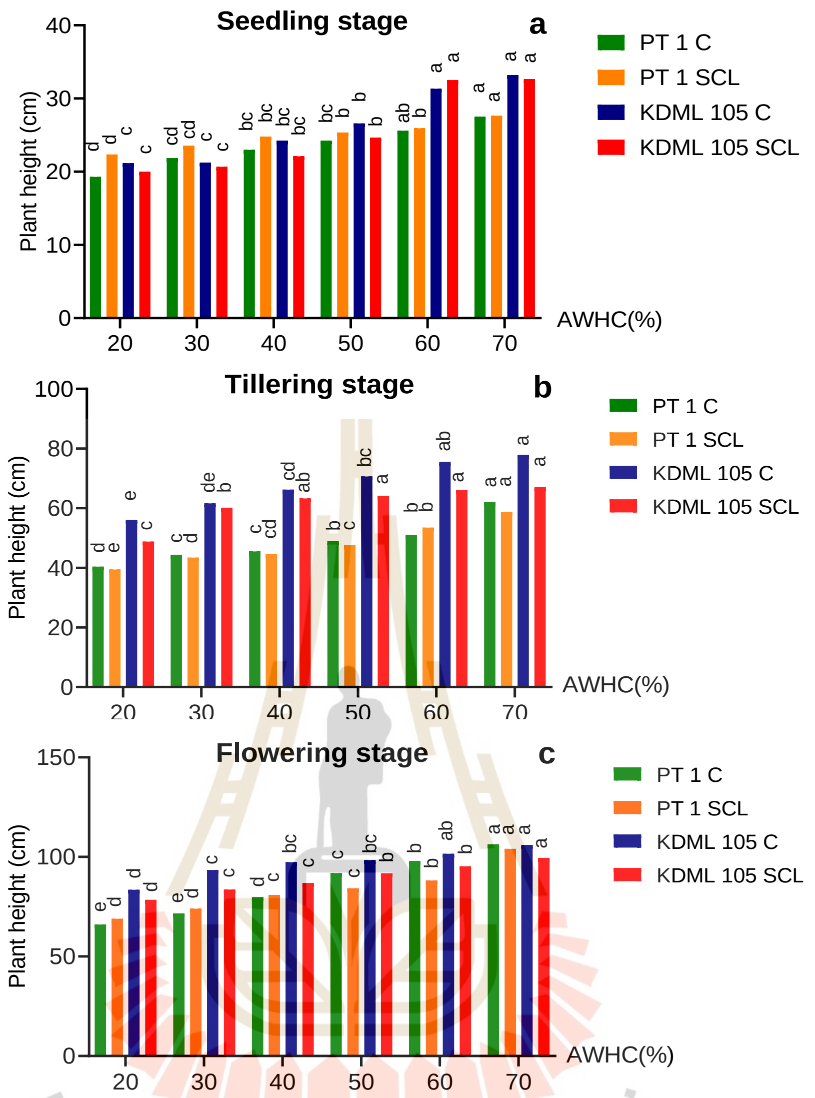


Figure 4.3 Average daily temperature and relative humidity throughout the experiment.

4.3.3 Morphological traits

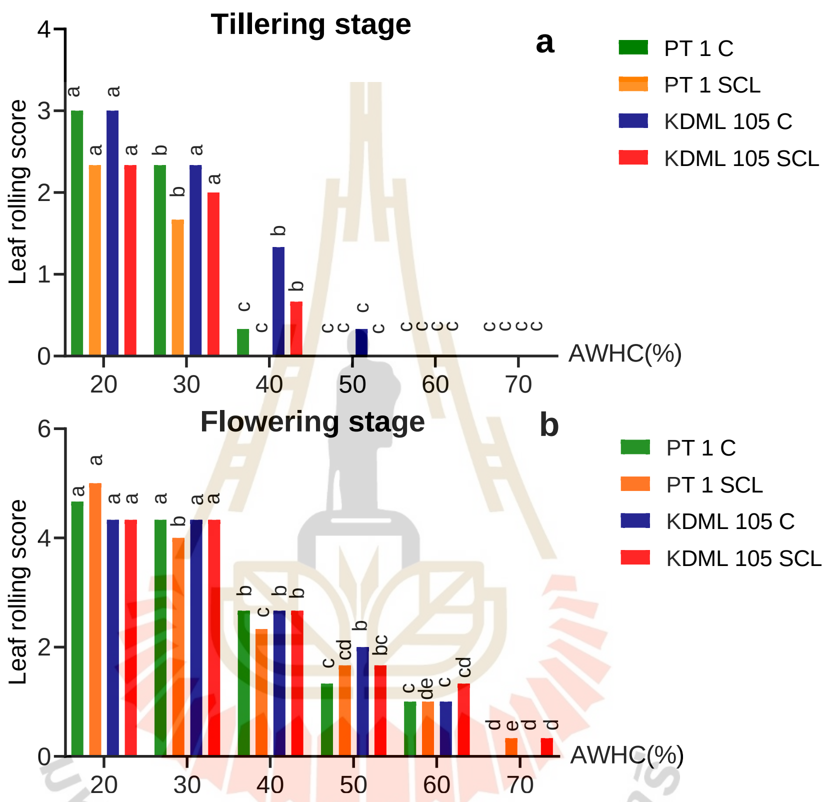
- **Plant height** of both cultivars decreased when soil moisture levels decreased at all growth stages in both soils. Plant height of PT 1 in C soil decreased from 27.53 to 19.30 cm at 70 to 20% AWHC at seedling stage. PT 1 in SCL soil, it significantly decreased from 27.63 to 23.57 cm at 70 to 30% AWHC then reduced to 22.37 cm at 20% AWHC. Plant height of KDML 105 in C soil significantly decreased from 33.20 to 24.27 cm at 70 to 40% AWHC then remained stable until 20% AWHC (21.17 cm). While KDML 105 in SCL soil dramatically decreased from 32.67 to 20.00 cm at 70 to 20% AWHC (Figure 4.4a).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.4 Response of plant height to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

At tillering stage, PT 1 in C soil dramatically decreased from 62.10 to 44.40 cm at 70 to 30% AWHC, then decreased to 40.40 cm at 20% AWHC. For PT 1 in SCL soil, it decreased from 58.77 to 47.70 cm at 70 to 50% AWHC, then it continuously decreased to 39.40 cm at 20% AWHC. For KDML 105 in C soil, it steadily decreased from 77.93 to 56.07 cm at 70 to 20% AWHC, while in SCL soil, it gradually decreased from 67.07 to 60.13 cm at 70 to 30% AWHC, then dramatically decreased to 48.80 cm at 20% AWHC (Figure 4.4b). At flowering stage, plant height of PT 1 in C soil significantly decreased from 106.33 to 91.90 cm at 70 to 50% AWHC, then it dramatically decreased to 66.10 cm at 20% AWHC while in SCL soil, it decreased from 104.07 to 68.93 cm at 70 to 20% AWHC. Besides, KDML 105 in C soil dramatically decreased from 106.03 to 83.57 cm at 70 to 20% AWHC. For KDML 105 in SCL soil, it steadily decreased from 99.53 to 78.50 cm at 70 to 20% AWHC (Figure 4.4c).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.5 Response of leaf rolling score to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

- **Leaf rolling score** increased when soil moisture levels decreased throughout the experiment in both cultivars and soils. Leaf rolling score had no significant difference and not appeared at seedling stage. At tillering stage, PT 1 in C soil remained stable at 0.00 from 70 to 50% AWHC then significantly increased to 3.00 at 20% AWHC. PT 1 in SCL soil result remained stable at 0.00 between 70, 60, 50, and 40% AWHC then increased from 1.67 to 2.33 at 30 to 20% AWHC. KDML 105 in C soil remained stable at 0.00 between 70 and 60% AWHC then increased to 3.00 at 20% AWHC while SCL soil, it remained stable at 0.00 from 70 to 50% AWHC then increased to 2.33 at 20% AWHC (Figure 4.5a). At flowering stage, PT 1 in C soil significantly increased from 0.00 to 4.67 at 70 to 20% AWHC while SCL soil result increased from 0.33 to 5.00 at 70 to 20% AWHC. Similarly, KDML 105 in C soil significantly increased from 0.00 to 2.67 at 70 to 40% AWHC and remained stable at 4.33 between 30 and 20% AWHC. KDML 105 in SCL soil result also increased from 0.33 to 4.33 at 70 to 20% AWHC (Figure 4.5b).

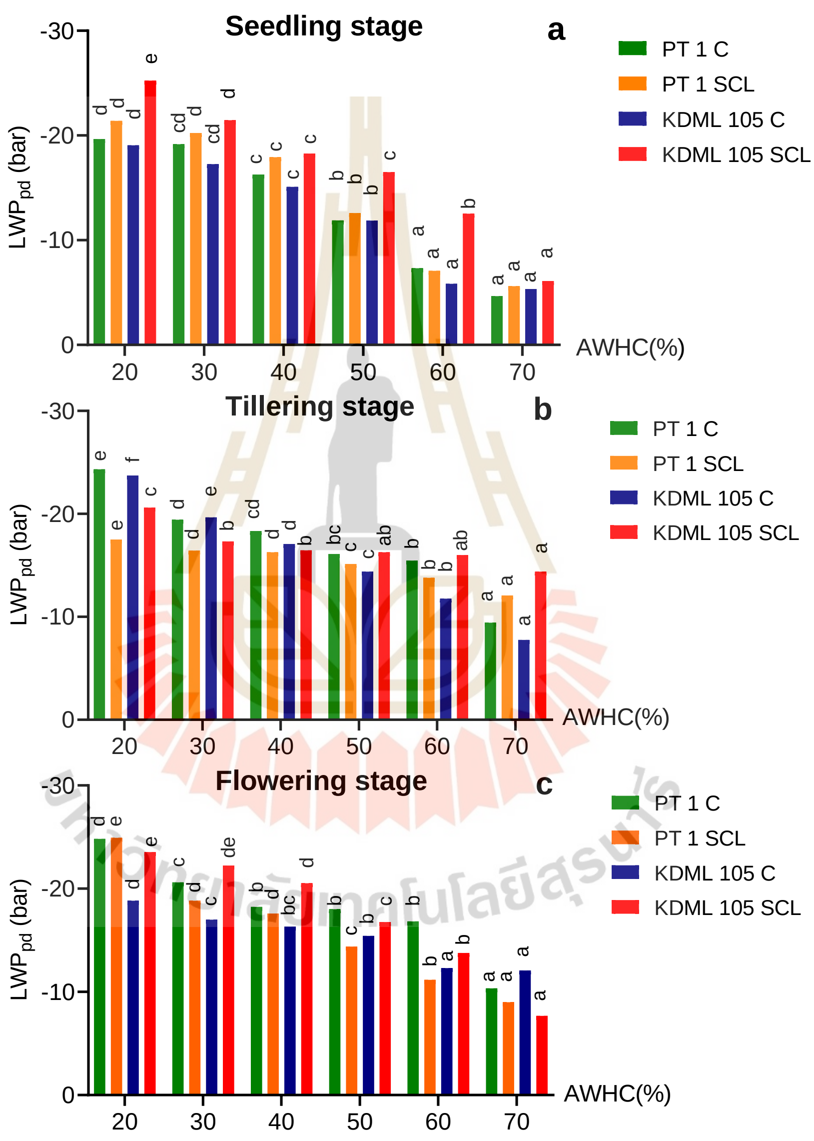
In this experiment, plant height decreased while leaf rolling score increased when soil moisture levels decreased in both cultivars and soils. Drought reduced plant growth by inhibiting physiological processes that led to reduced plant height and increased leaf rolling which consequently resulted to the reduction in leaf surface area and leaf elongation (Mustikarini et al., 2022). These results agreed with Umego et al. (2020) who recorded that plant height decreased under water stress compared to non-stress conditions except for rice tolerant cultivar, while leaf rolling score significantly increased under stress compared to normal conditions in all cultivars.

Similar to Maurya et al. (2021) who found that drought stress significantly reduced plant height and increased leaf rolling in all rice genotypes. Moreover, Pavithra and Vengadessan (2020) who revealed that plant height significantly decreased while leaf rolling and leaf drying increased under drought at vegetative stage. These results were opposite to Mustikarini et al. (2022) experiment, who reported that plant height was not significantly different under drought, while leaf rolling and leaf drying reduction increased in all rice cultivars especially at flowering stage that is similar to this experiment.

4.3.4 Physiological characteristics

- Predawn leaf water potential (LWP_{pd}) of both cultivars decreased when soil moisture levels decreased throughout the rice life cycle in both soils. At seedling stage, LWP_{pd} of PT 1 in C soil significantly decreased from -4.57 to -11.90 bar at 70 to 50% AWHC then dramatically decreased to -19.67 bar at 20% AWHC. Similar result was observed in SCL soil, LWP_{pd} decreased from -5.60 to -7.07 bar at 70 to 60% AWHC then dramatically decreased to -21.40 bar at 20% AWHC. Besides, KDML 105 in

C soil gradually decreased from -5.33 to -5.83 bar at 70 to 60% AWHC then dramatically decreased to -11.87, -15.10, -17.27, and -19.07 bar at 50, 40, 30, and 20% AWHC, respectively. KDML 105 in SCL result dramatically decreased from -6.10 to -16.50 bar at 70 to 50% AWHC then decreased to -18.27, -21.47, and -25.23 bar at 40, 30, and 20% AWHC, respectively (Figure 4.6a).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

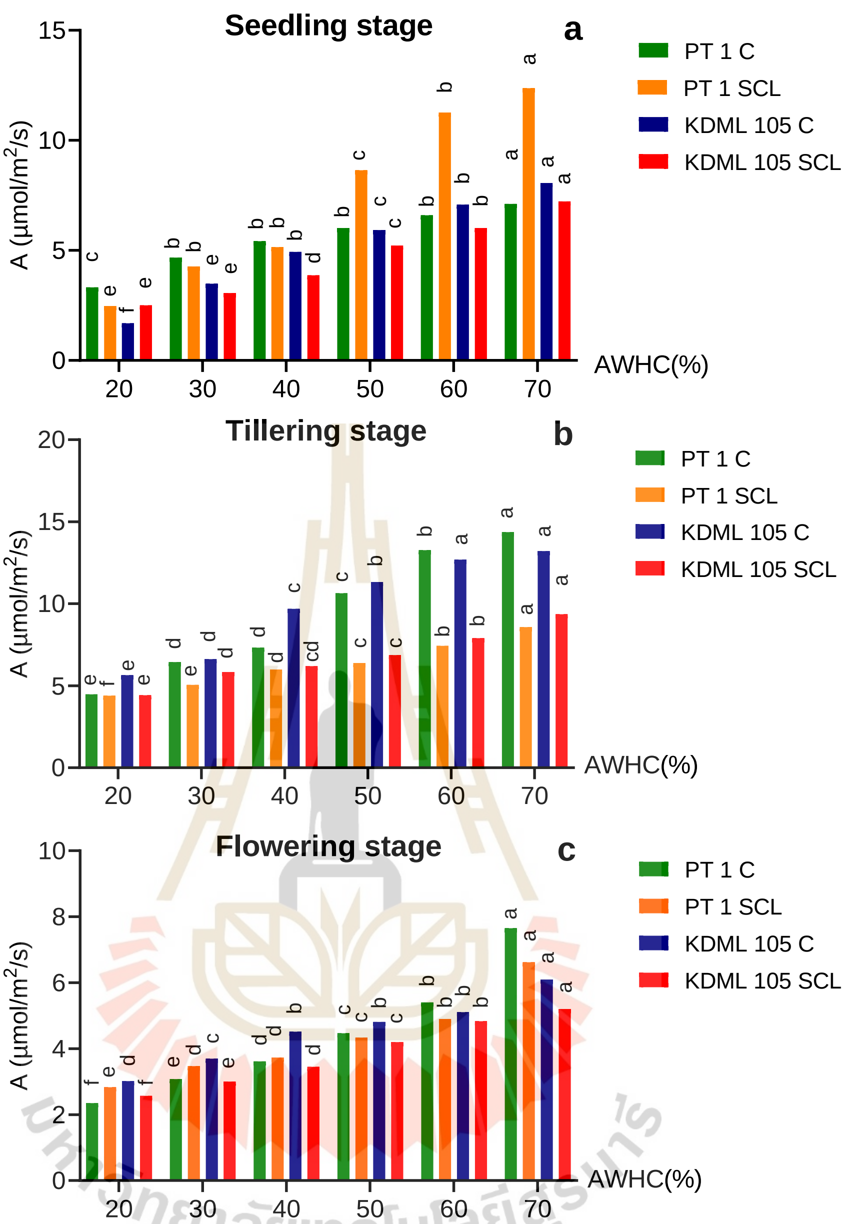
Figure 4.6 Response of LWP_{pd} to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

At tillering stage, LWP_{pd} of PT 1 in C soil dramatically decreased from -9.43 to -15.47 bar from 70 to 60% AWHC then significantly decreased to -19.43 and -24.33 bar at 30 and 20% AWHC. PT 1 in SCL soil, it steadily decreased from -12.07 to -17.50 bar at 70 to 20% AWHC. Besides, LWP_{pd} of KDML 105 in C soil dramatically decreased from -7.77 to -23.73 bar at 70 to 20% AWHC while SCL soil result significantly decreased from -14.40 to -17.33 bar at 70 to 30% AWHC then continuously decreased to -20.60 bar at 20% AWHC (Figure 4.6b).

At flowering stage, LWP_{pd} of PT 1 in C soil dramatically decreased from -10.33 to -16.83 bar at 70 to 60% AWHC then it steadily decreased to -18.23 bar at 40% AWHC after that decreased to -24.83 bar at 20% AWHC while PT 1 in SCL soil significantly decreased from -9.00 to -24.63 bar at 70 to 20% AWHC. However, KDML 105 in C soil remained stable at -12.07 and -12.30 bar between 70 and 60% AWHC then significantly decreased to -18.83 bar at 20% AWHC. KDML 105 in SCL soil result dramatically decreased from -7.67 to -16.77 bar at 70 to 50% AWHC then continuously decreased to -23.53 bar at 20% AWHC (Figure 4.6c).

- Net photosynthesis rate (A), the results showed that A of both cultivars decreased when soil moisture levels decreased throughout the rice life cycle in both soils. At seedling stage, A of PT 1 in C soil significantly decreased from 7.11 to 3.32 $\mu mol/m^2/s$ at 70 to 20% AWHC. PT 1 in SCL soil result decreased from 12.37 to 5.15 $\mu mol/m^2/s$ at 70 to 40% AWHC and it steadily decreased to 2.48 $\mu mol/m^2/s$ at 20% AWHC. KDML 105 in C soil result decreased from 8.06 to 5.93 $\mu mol/m^2/s$ at 70 to 50% AWHC then dramatically decreased to 1.69 $\mu mol/m^2/s$ at 20% AWHC. KDML 105 in SCL soil significantly decreased from 7.23 to 2.51 $\mu mol/m^2/s$ at 70 to 20% AWHC (Figure 4.7a).

At tillering stage, A of PT 1 in C soil significantly decreased from 14.37 to 10.64 $\mu mol/m^2/s$ at 70 to 50% AWHC then dramatically decreased to 4.48 $\mu mol/m^2/s$ at 20% AWHC. For PT 1 in SCL soil, it steadily decreased from 8.58 to 4.39 $\mu mol/m^2/s$ at 70 to 20% AWHC. A of KDML 105 in C soil decreased from 13.22 to 9.69 $\mu mol/m^2/s$ at 70 to 40% AWHC then continuously decreased to 5.65 $\mu mol/m^2/s$ at 20% AWHC while SCL result significantly decreased from 9.36 to 4.42 $\mu mol/m^2/s$ at 70 to 20% AWHC (Figure 4.7b).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.7 Response of A to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

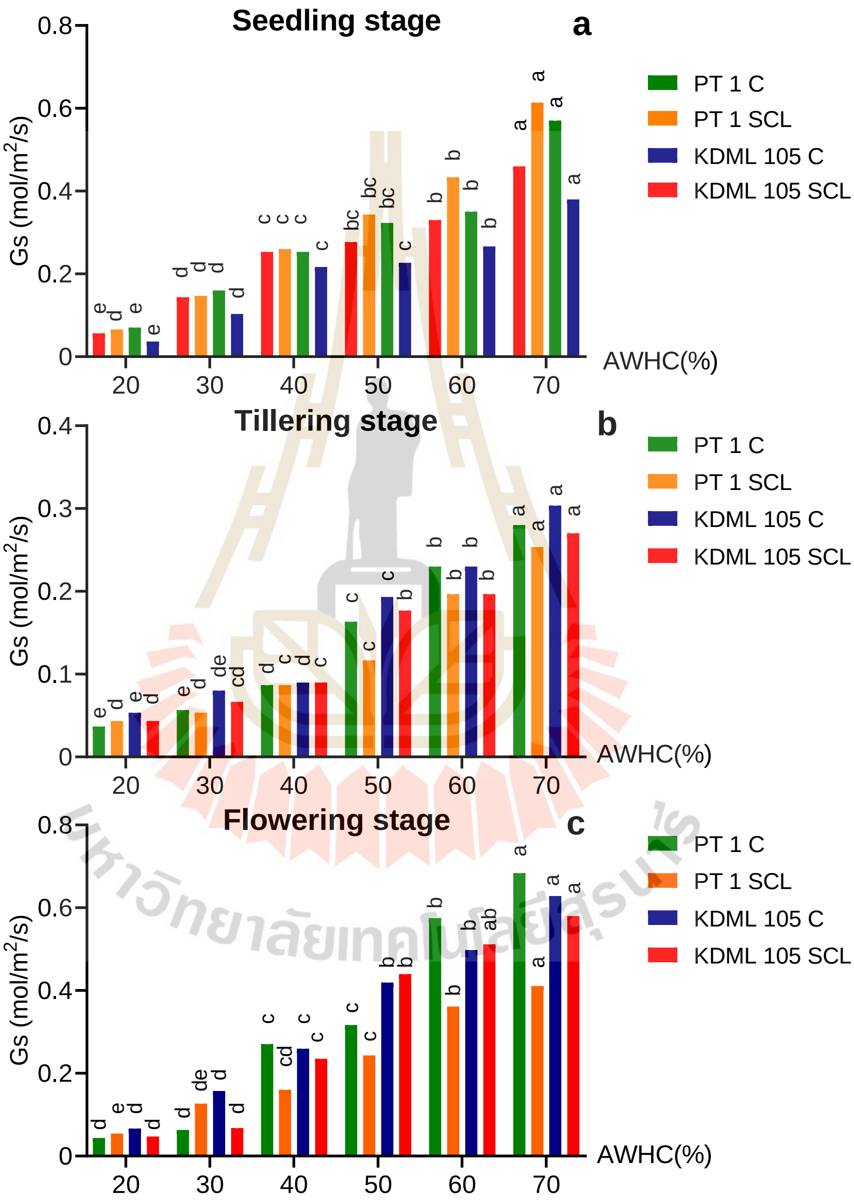
- **Stomatal conductance (g_s)**, the results showed that g_s of both cultivars decreased when soil moisture levels decreased throughout the rice life cycle in both soils. At seedling stage, PT 1 in C soil dramatically decreased from 0.57 to 0.07 mol/m^2/s at 70 to 20% AWHC. Similar to PT 1 in SCL soil significantly decreased from 0.61 to 0.34 mol/m^2/s at 70 to 50% AWHC then rapidly decreased to 0.06 mol/m^2/s at

20% AWHC. Besides, KDML 105 in C soil decreased from 0.38 to 0.22 mol/m^2/s at 70 to 40% AWHC then significantly decreased to 0.04 mol/m^2/s at 20% AWHC. KDML 105 in SCL soil decreased from 0.46 to 0.25 mol/m^2/s at 70 to 40% AWHC then dramatically decreased to 0.06 mol/m^2/s at 20% AWHC (Figure 4.8a).

At tillering stage, g_s of PT 1 in C soil dramatically decreased from 0.28 to 0.04 mol/m^2/s at 70 to 20% AWHC while SCL soil significantly decreased from 0.25 to 0.12 mol/m^2/s at 70 to 50% AWHC then it steadily decreased to 0.04 mol/m^2/s at 20% AWHC. KDML 105 in C soil dramatically decreased from 0.30 to 0.05 mol/m^2/s at 70 to 20% AWHC. KDML 105 in SCL soil decreased from 0.27 to 0.18 mol/m^2/s at 70 to 50% AWHC then dramatically decreased to 0.09, 0.07, and 0.04 mol/m^2/s at 40, 30, and 20% AWHC (Figure 4.8b). At flowering stage, g_s of PT 1 in C soil dramatically decreased from 0.68 to 0.27 mol/m^2/s at 70 to 40% AWHC then continuously decreased to 0.04 mol/m^2/s at 20% AWHC while SCL soil result significantly decreased from 0.41 to 0.36 mol/m^2/s at 70 to 60% AWHC then gradually decreased from 0.24 to 0.05 mol/m^2/s at 50 to 20% AWHC. KDML 105 in C soil result dramatically decreased from 0.63 to 0.50 mol/m^2/s at 70 to 60% AWHC then dramatically decreased to 0.07 mol/m^2/s at 20% AWHC. However, SCL soil result decreased from 0.58 to 0.24 mol/m^2/s at 70 to 40% AWHC then dramatically decreased to 0.05 mol/m^2/s at 20% AWHC (Figure 4.8c).

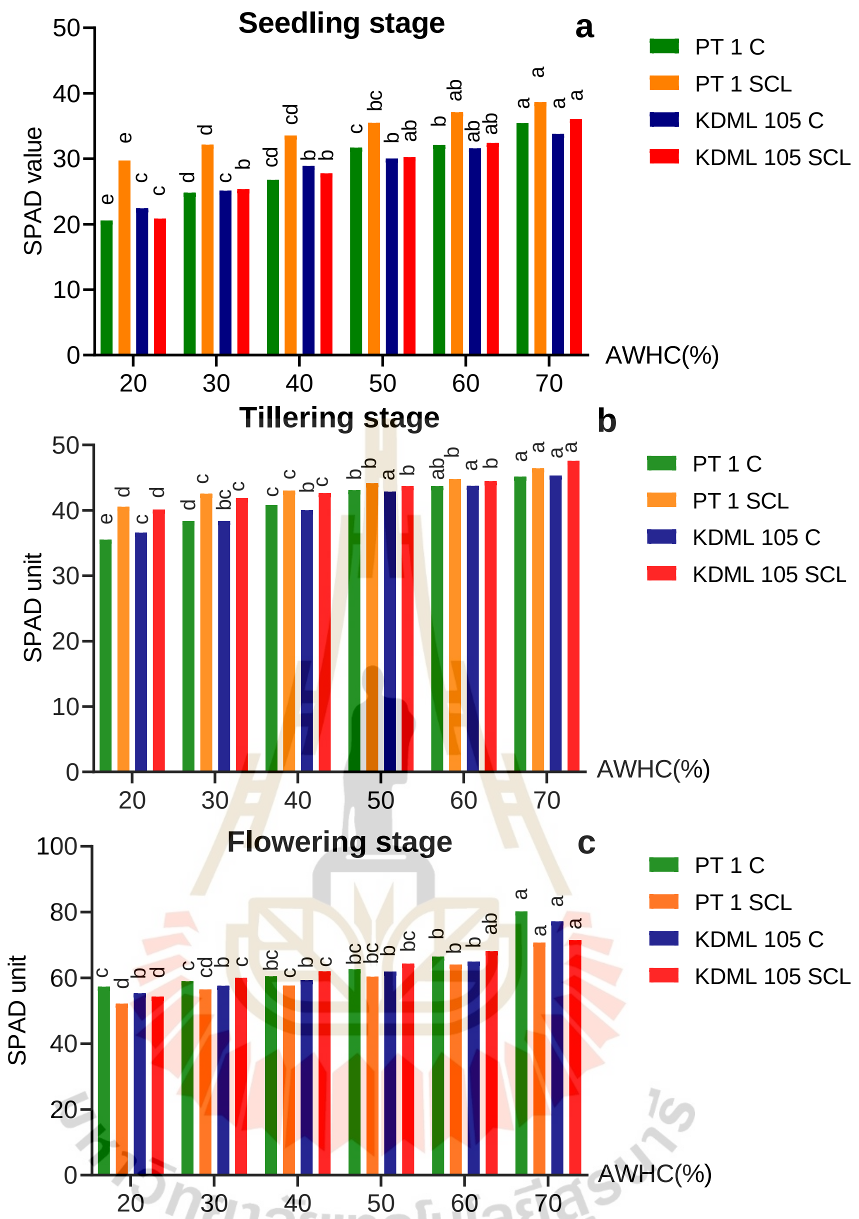
- SPAD chlorophyll reading, the results showed that SPAD value of both cultivars decreased when soil moisture levels decreased throughout the rice life cycle in both soils. At seedling stage, SPAD value of PT 1 in C soil significantly decreased from 35.47 to 26.77 at 70 to 40% AWHC then decreased to 20.57 at 20% AWHC. PT 1 in SCL soil significantly decreased from 38.67 to 29.73 at 70 to 20% AWHC. Similar to KDML 105 in C soil decreased from 33.80 to 22.43 at 70 to 20% AWHC while SCL soil result decreased from 36.07 to 20.87 at 70 to 20% AWHC (Figure 4.9a). At tillering stage, SPAD value of PT 1 in C soil gradually decreased from 45.17 to 35.53 at 70 to 20% AWHC while SCL soil result significantly increased from 46.43 to 40.53 at 70 to 20% AWHC. KDML 105 in C result decreased from 45.33 to 36.60 at 70 to 20% AWHC which corresponded to SCL soil result significantly decreased from 47.57 to 40.13 at 70 to 20% AWHC (Figure 4.9b). At flowering stage, SPAD value of PT 1 in C soil dramatically decreased from 80.23 to 66.50 at 70 to 60% AWHC then continuously decreased to

57.30 at 20% AWHC similar to SCL soil result decreased from 70.73 to 52.13 at 70 to 20% AWHC. Besides, KDML 105 in C soil significantly decreased from 77.19 to 55.33 at 70 to 20% AWHC and SCL soil result decreased from 71.47 to 54.30 at 70 to 20% AWHC (Figure 4.9c).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

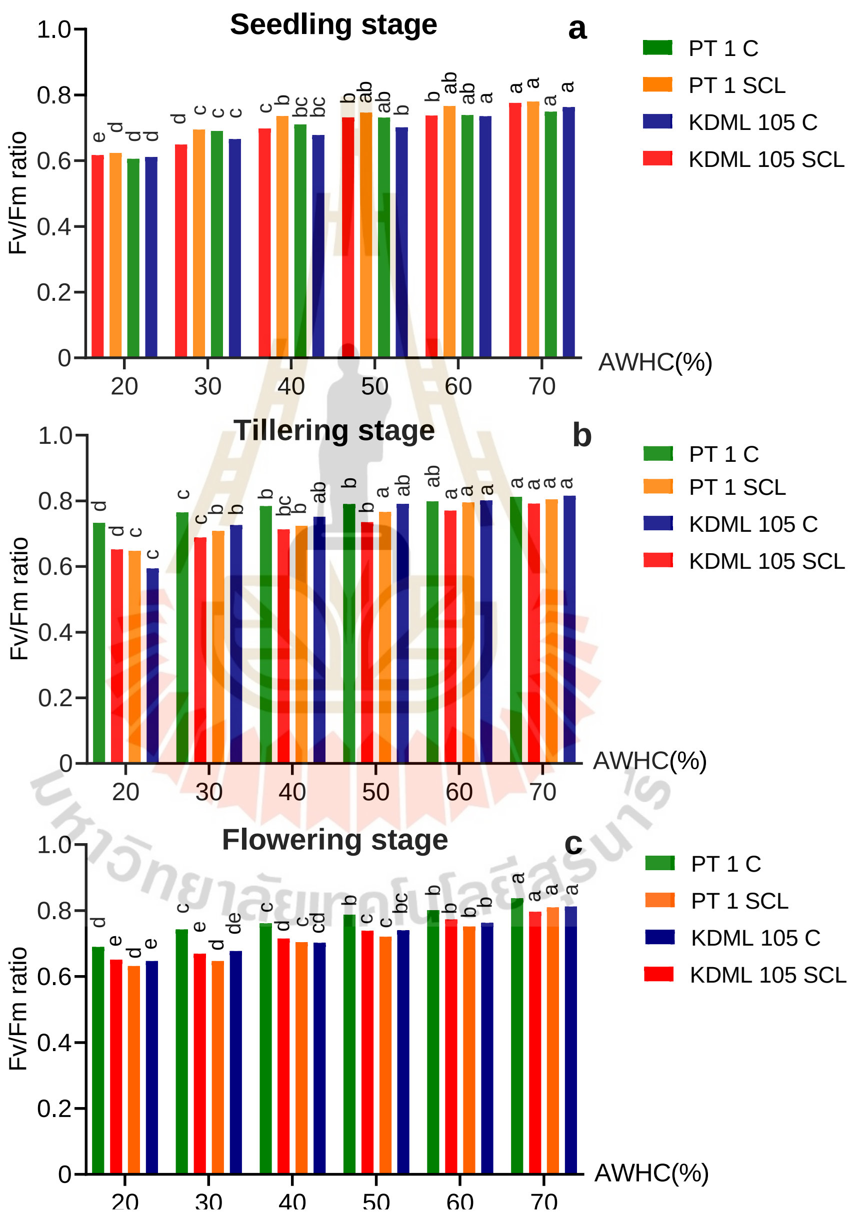
Figure 4.8 Response of g_s to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.9 Response of SPAD value to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

- Chlorophyll fluorescence (Fv/Fm ratio), Fv/Fm is a ratio from variable fluorescence divided by maximum fluorescence that represents the maximum potential quantum efficiency of Photosystem II. The optimal Fv/Fm ratio in all plant species is range from 0.79 to 0.84 if the value decreases it could imply that plant has shown sign of stress (Maxwell & Johnson, 2000). Fv/Fm ratio of both cultivars decreased when soil moisture levels decreased at all growth stages in both soils. At seedling stage, PT 1 in C soil result gradually decreased from 0.749 to 0.606 at 70 to 20% AWHC while SCL soil significantly decreased from 0780 to 0.624 at 70 to 20% AWHC. KDML 105 in C soil result decreased from 0.763 to 0.611 at 70 to 20% AWHC and in SCL soil result gradually decreased from 0.776 to 0.617 at 70 to 20% AWHC (Figure 4.10a).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.10 Response of Fv/Fm ratio to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

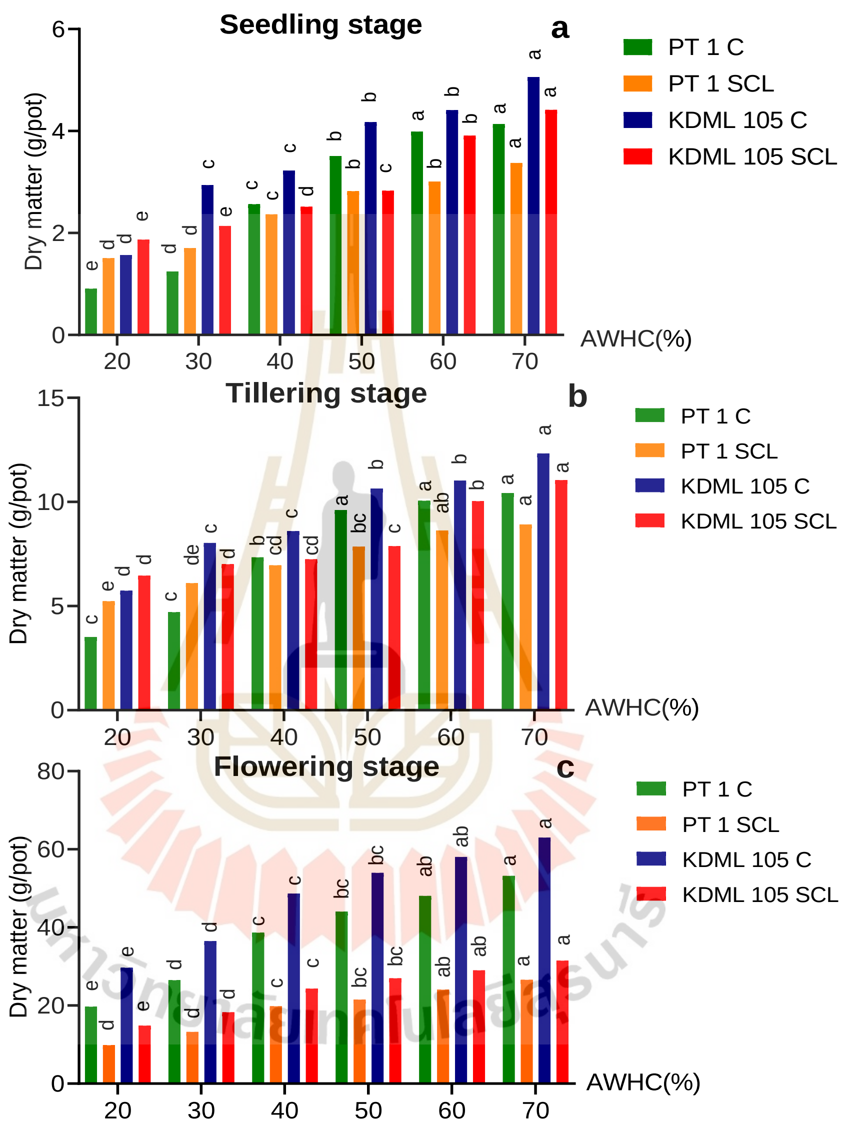
At tillering stage, Fv/Fm ratio of PT 1 in C soil significantly decreased from 0.813 to 0.733 at 70 to 20% AWHC. Similar to PT 1 in SCL soil result decreased from 0.805 to 0.708 at 70 to 30% AWHC then dropped to 0.648 at 20% AWHC. KDML 105 in C soil significantly decreased from 0.816 to 0.594 at 70 to 20% AWHC which corresponded to SCL soil result significantly decreased from 0.792 to 0.652 at 70 to 20% AWHC (Figure 4.10b). At flowering stage, PT 1 in C soil significantly decreased from 0.837 to 0.690 at 70 to 20% AWHC and in SCL soil, it steadily decreased from 0.809 to 0.632 at 70 to 20% AWHC. Fv/Fm ratio of KDML 105 in C soil significantly decreased from 0.813 to 0.647 at 70 to 20% AWHC while in SCL soil, it steadily decreased from 0.797 to 0.651 at 70 to 20% AWHC (Figure 4.10c).

In this experiment, the results showed that LWP_{pd}, A, g_s, SPAD value, and Fv/Fm ratio of both cultivars decreased when soil moisture levels decreased throughout experiment in both soils. Drought affected plant water absorption and limited amount of water that led to the reduction in leaf water potential (Reddy et al., 2021). Under water stress, the plant accumulates compatible solutes such as sugars and amino acid to reduce osmotic potential in guard cell that resulting in stomatal closure, limited gas exchange, and reduced photosynthesis activities such as, A, g_s, SPAD chlorophyll index, and chlorophyll fluorescence) (Tanguilig et al., 1987; Panda et al., 2021). These results were similar to Larkunthod et al. (2018) who found that LWP, relative water content, osmotic potential, and DM under drought significant decreased except for SPAD value in all rice cultivars at seedling stage.

Yang et al. (2019) also suggested that drought had a strong influence on rice physiological traits and yield at flowering stage especially in net photosynthetic rate, g_s, and LWP significantly decreased under stress. These results are also in agreement with Kumar et al. (2020) who revealed that photosynthetic rate, g_s, transpiration rate, and total chlorophyll significantly declined ($p<0.05$) under multi-stage drought conditions. Additionally, SPAD value and chlorophyll florescence decreased due to drought effect on dysfunction and destruction function in thylakoid structural membrane which is related to degeneration in chlorophyll and disturbed photosynthesis activities (Melkozernov & Blankenship, 2006; Batool et al., 2022). Moreover, Mishra et al. (2018) recorded that leaf photosynthetic rate, photochemical efficiency of photosystem II (Fv/Fm), and SPAD chlorophyll index significantly decreased after stress for 5 and 10 days compared to control treatment.

4.3.5 Yield and yield components

- Dry matter (DM), the results showed that DM of both cultivars decreased when soil moisture levels decreased throughout the experiment in both soils.



*The different letters indicate statistical significance according to DMRT ($P \leq 0.05$).

Figure 4.11 Response of DM to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

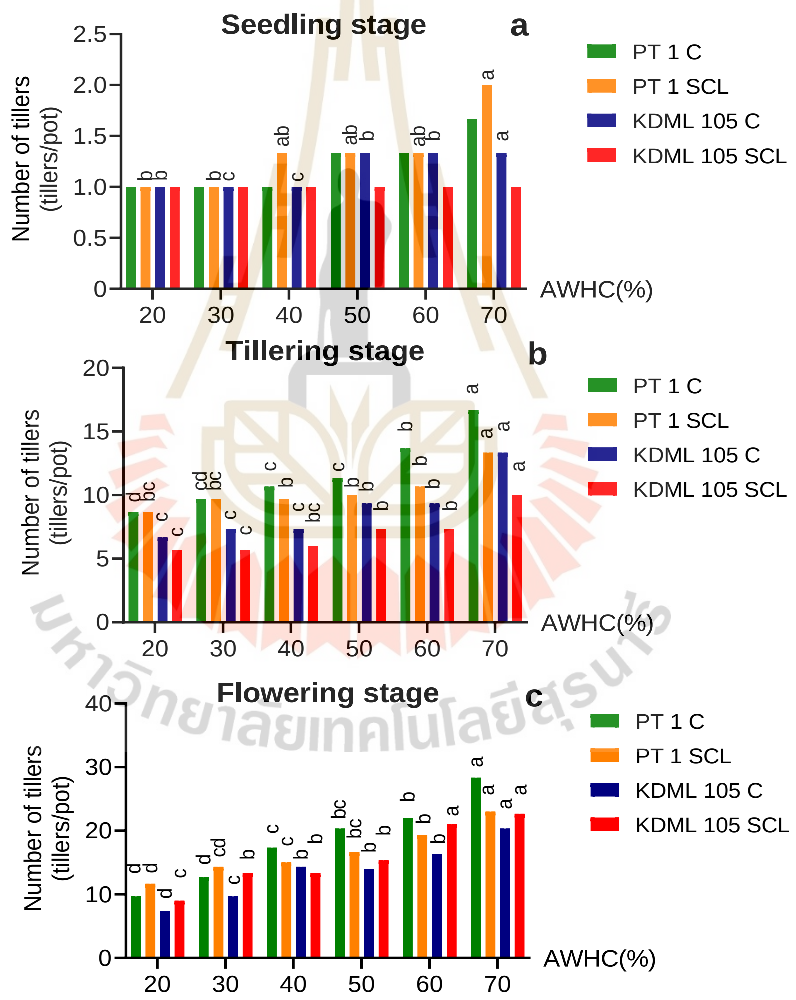
At seedling stage, DM of PT 1 in C soil decreased from 4.14 to 2.57 g/pot at 70 to 40% AWHC then dramatically decreased to 0.09 g/pot at 20% AWHC while SCL soil result decreased from 3.38 to 1.51 g/pot at 70 to 20% AWHC. KDML 105 in C soil dramatically decreased from 5.06 to 1.57 g/pot at 70 to 20% AWHC similar to SCL soil result it significantly decreased from 4.42 to 1.87 g/pot at 70 to 20% AWHC (Figure 4.11a). At tillering stage, PT 1 in C soil significantly decreased from 10.43 to 9.62 g/pot at 70 to 50% AWHC then dramatically decreased to 3.52 g/pot at 20% AWHC while, SCL soil result significantly decreased from 8.92 to 5.23 g/pot at 70 to 20% AWHC. KDML 105 in C soil result decreased from 12.33 to 5.74 g/pot at 70 to 20% AWHC however, in SCL soil result dramatically decreased from 11.05 to 6.46 g/pot at 70 to 20% AWHC (Figure 4.11b).

At flowering stage, DM of PT 1 in C soil significantly decreased from 53.19 to 38.67 g/pot at 70 to 40% AWHC then dropped to 26.48 and 19.70 g/pot at 30 and 20% AWHC. Similarly, PT 1 in SCL soil result decreased from 26.60 to 13.25 g/pot at 70 to 30% AWHC then dramatically decreased to 9.85 g/pot at 20% AWHC. Besides KDML 105 in C soil, it steadily decreased from 62.98 to 29.65 g/pot at 70 to 20% AWHC while SCL soil result significantly decreased from 31.47 to 14.83 g/pot at 70 to 20% AWHC (Figure 4.11c).

- **Number of tillers per pot** of both cultivars decreased when soil moisture levels decreased in both soils. At seedling stage, number of tillers of PT 1 in C soil decreased from 1.67 to 1.33 tillers/pot at 70 to 50% AWHC and remained stable to 1.00 tillers/pot at 40, 30, and 20% AWHC. PT 1 in SCL soil result decreased from 2.00 to 1.33 tillers/pot at 70 to 60% AWHC and remained stable to 1.33 tillers/pot between 50, 40, and 30% AWHC then reduced to 1.00 tillers/pot at 30 and 20% AWHC. KDML 105 in C soil remained stable to 1.33 tillers/pot at 70, 60, and 50% AWHC then reduced to 1.00 tillers/pot at 40, 30, and 20% AWHC while KDML 105 in SCL soil remained stable to 1.00 tillers/pot at 70 to 20% AWHC (Figure 4.12a).

At tillering stage, PT 1 in C soil result significantly decreased from 16.67 to 13.67 tillers/pot at 70 to 60% AWHC then gradually decreased to 8.67 tillers/pot at 20% AWHC. PT 1 in SCL soil result significantly decreased from 13.33 to 10.00 tillers/pot at 70 to 50% AWHC then continuously reduced to 8.67 tillers/pot at 20% AWHC. KDML 105 in C soil result decreased from 13.33 to 6.67 tillers/pot at 70 to 20% AWHC. However, KDML 105 in SCL soil significantly decreased from 10.00 to 7.33 tillers/pot at

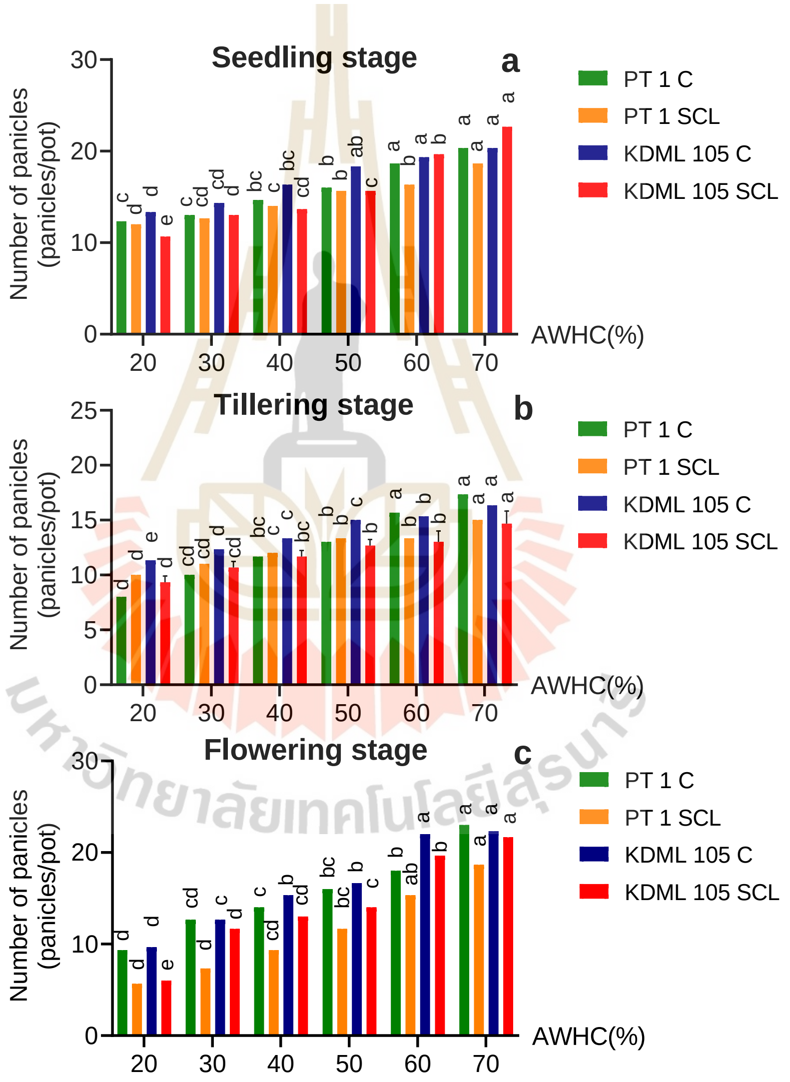
70 to 60% AWHC then continuously decreased to 5.67 tillers/pot at 20% AWHC (Figure 4.12b). At flowering stage, PT 1 in C soil significantly decreased from 28.33 to 20.33 tillers/pot at 70 to 50% AWHC then dropped to 9.67 tillers/pot at 20% AWHC. Similarly, PT 1 in SCL soil decreased from 23.00 to 19.33 tillers/pot at 70 to 60% AWHC then dramatically decreased to 11.67 tillers/pot at 20% AWHC. Besides KDML 105 in C soil, it steadily decreased from 20.33 to 7.33 tillers/pot at 70 to 20% AWHC while SCL soil result significantly decreased from 22.67 to 15.33 tillers/pot at 70 to 50% AWHC then dramatically decreased to 9.00 tillers/pot at 20% AWHC (Figure 4.12c).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.12 Response of number of tillers to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

- **Number of panicles per pot** of both cultivars decreased when soil moisture levels decreased in both soils. At seedling stage, PT 1 in C soil result dramatically decreased from 20.33 to 13.33 panicles/pot at 70 to 20% AWHC and in SCL soil decreased from 18.67 to 12.00 panicles/pot at 70 to 20% AWHC. KDML 105 in C soil decreased from 20.00 to 13.33 panicles/pot at 70 to 20% AWHC. Besides, KDML 105 in SCL soil dramatically decreased from 22.67 to 13.00 panicles/pot at 70 to 30% AWHC then decreased to 10.67 panicles/pot at 20% AWHC (Figure 4.13a).



*The different letters indicate statistical significance according to DMRT (P≤0.05).

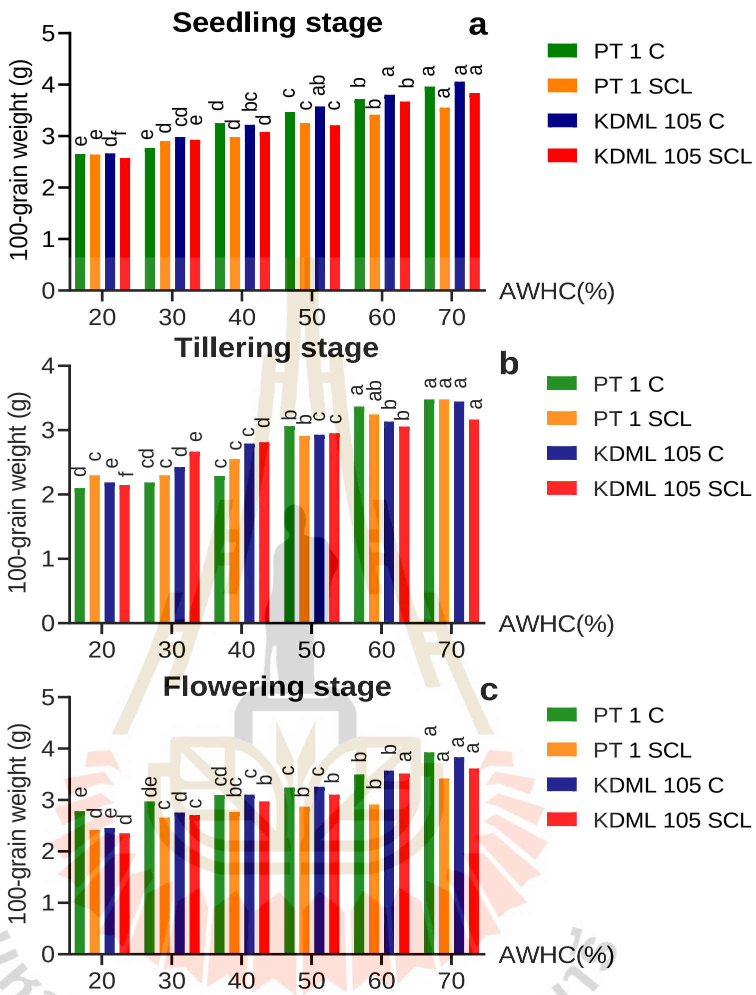
Figure 4.13 Response of number of panicles to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

At tillering stage, number of panicles of PT 1 in C soil decreased from 17.33, 15.67, 13.00, 11.67, 10.00, and 8.00 panicles/pot at 70, 60, 50, 40, 30, and 20% AWHC, respectively while in SCL soil significantly decreased from 15.00 to 10.00 panicles/pot at 70 to 20% AWHC. KDML 105 in C soil gradually decreased from 16.33, 15.33, 15.00, 13.33, 12.33 and 11.33 panicles/pot at 70, 60, 50, 40, 30, and 20% AWHC, respectively while in SCL soil decreased from 14.67 to 10.67 panicles/pot at 70 to 30% AWHC then reduced to 9.33 panicle/pot at 20% AWHC (Figure 4.13b).

At flowering stage, PT 1 in C soil result dramatically decreased from 23.00 to 18.00 panicles/pot at 70 to 60% AWHC then it decreased to 9.33 panicles/pot at 20% AWHC. PT 1 in SCL soil result decreased from 18.67 to 15.33 panicles/pot at 70 to 60% AWHC then it continuously decreased to 5.67 panicles/pot at 20% AWHC. KDML 105 in C soil decreased from 22.33 to 22.00 panicles/pot at 70 to 60% AWHC then dramatically decreased to 9.67 panicles/pot at 20% AWHC. However, KDML 105 in SCL soil dramatically decreased from 21.67 to 14.00 panicles/pot at 70 to 50% AWHC then it steadily decreased to 11.67 panicles/pot at 30% AWHC after that dropped to 6.00 panicles/pot at 20% AWHC (Figure 4.13c).

- **100-grain weight**, the results showed that grain weight of both cultivars decreased when soil moisture levels decreased in both soils. Grain weight of PT 1 in C soil significantly decreased from 3.96 to 3.25 g at 70 to 40% AWHC then reduced to 2.77 and 2.65 g at 30 and 20% AWHC. Similar to PT 1 in SCL soil result decreased from 3.55 to 2.98 g at 70 to 40% AWHC after that reduced to 2.65 g at 20% AWHC. However, KDML 105 in C soil significantly decreased from 4.06 to 3.80 g at 70 to 60% AWHC then it continuously decreased to 3.22 g at 40% AWHC while in SCL soil result decreased from 3.83 to 2.92 g at 70 to 30% AWHC then reduced to 2.66 g at 20%AWHC (Figure 4.14a).

At tillering stage, PT 1 in C soil result significantly decreased from 3.48 to 2.10 g at 70 to 20% AWHC and in SCL soil decreased from 3.48 to 2.30 g at 70 to 20% AWHC. Similar to KDML 105 in C soil significantly decreased from 3.44 to 2.19 g at 70 to 20% AWHC and in SCL soil decreased from 3.16 to 2.15 g at 70 to 20% AWHC (Figure 4.14b). At flowering stage, PT 1 in C soil significantly reduced from 3.93 to 2.78 g at 70 to 20% AWHC and SCL soil result reduced from 3.42 to 2.42 g at 70 to 20% AWHC. Similar to KDML 105 in C soil significantly decreased from 3.83 to 2.46 g at 70 to 20% AWHC and in SCL soil reduced from 3.61 to 2.35 g at 70 to 20% AWHC (Figure 4.14c).

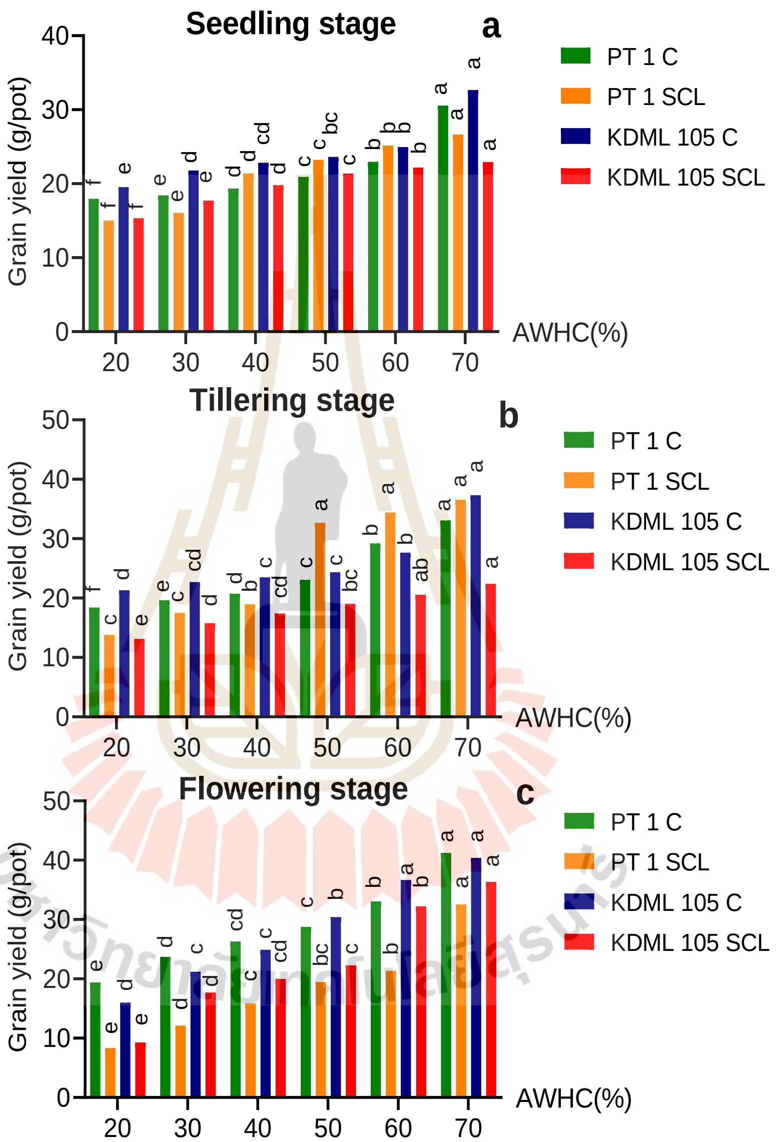


*The different letters indicate statistical significance according to DMRT (P≤0.05).

Figure 4.14 Response of 100-grain weight to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

- Grain yield per pot (GY), the results showed that GY of both cultivars decreased when soil moisture levels decreased in both soils. GY of PT 1 in C soil dramatically decreased from 30.56 to 22.93 g/pot at 70 to 60% AWHC then continuously decreased to 17.96 g/pot at 20% AWHC. Similar to PT 1 cultivar in SCL soil decreased from 26.61 to 21.36 g/pot at 70 to 40% AWHC. Then reduced to 14.98 g/pot at 20%

AWHC. KDML 105 in C soil dramatically decreased from 32.63 to 24.96 g/pot at 70 to 60% AWHC, then continuously decreased to 19.53 g/pot at 20% AWHC. KDML 105 in SCL soil result significantly decreased from 22.93 to 19.78 g/pot at 70 to 40% AWHC then it steadily decreased to 15.30 g/pot at 20% AWHC (Figure 4.15a).



*The different letters indicate statistical significance according to DMRT ($P \leq 0.05$).

Figure 4.15 Response of grain yield to different levels of soil moisture content in C and SCL soils at seedling stage (a), tillering stage (b), and flowering stage (c).

At tillering stage, GY of PT 1 in C soil dramatically decreased from 33.05 to 29.19 g/pot at 70 to 60% AWHC then continuously decreased to 18.41 g/pot at 20% AWHC. PT 1 in SCL soil result decreased from 36.57 to 32.65 g/pot at 70 to 50% AWHC then dramatically decreased to 13.77 g/pot at 20% AWHC. KDML 105 in C soil dramatically decreased from 37.31 to 27.65 g/pot at 70 to 60% AWHC then gradually decreased to 21.31 g/pot at 20% AWHC while in SCL soil decreased from 22.39 to 13.12 g/pot at 70 to 20% AWHC (Figure 4.15b).

At flowering stage, GY of PT 1 in C soil dramatically decreased from 41.24 to 28.78 g/pot at 70 to 50% AWHC then continuously decreased to 19.40 g/pot at 20% AWHC. Similar to the PT 1 in SCL soil result dramatically decreased from 32.52 to 19.43 g/pot at 70 to 50% AWHC then continuously reduced to 12.11 and 8.32 g/pot at 30 and 20% AWHC. KDML 105 in C soil decreased from 40.38 to 36.63 g/pot at 70 to 60% AWHC then gradually decreased to 21.20 g/pot at 30% AWHC after that dramatically decreased to 15.98 g/pot at 20% AWHC. KDML 105 in SCL soil significantly decreased from 36.30 to 22.29 g/pot at 70 to 50% AWHC then it steadily decreased to 17.70 g/pot at 30% AWHC after that dramatically decreased to 9.28 g/pot at 20% AWHC (Figure 4.15c).

In this experiment, yield and yield components including DM, number of tillers, number of panicles, 100-grain weight, and GY decreased when soil moisture levels decreased in both soils and cultivars. Drought reduced plant growth by inhibiting morphological, physiological, and biochemical processes which resulted in yield and yield components reduction (Zhang et al., 2019). Under drought conditions, GY reduction mostly resulted from the decreased yield components including grain weight and fertile panicles particularly in GY at flowering stage in this experiment (Sarhadi et al., 2015; Mitsuya et al., 2019). Total GY reduction of PT was 46.16% in C and 60.16% in SCL soils and KDML 105 was 47.8% in C and 49.7% in SCL soils when soil moisture decreased from 70 to 20% AWHC during the experiment.

The similar response of rice to drought was also reported by several researchers such as Sarvestani et al. (2008) and Kamarudin et al. (2018) who found that water stress significantly decreased DM, GY, and yield components of rice more than 50% compared to saturated condition due to A and DM reduction. Rao et al. (2019) and Yang et al. (2019) also reported that the reduction of rice yield and yield components such as total number of grains, filled grains, number of spikelets per panicle, 1000-grain weight, GY caused by drought at flowering stage by more than 23% compared with non-stress condition. However, the magnitudes of response varied among rice cultivars and growth stage. In this experiment, KDML 105 was a little more sensitive to drought than PT 1 in terms of GY reduction particularly in flowering stage.

In addition, KDML 105 is capable to grow under drought and well adapts to rainfed area, however rice grains of KDML 105 are easy to fall off the panicle under stress conditions. The appropriate planting season of KDML 105 is between August to November in Thailand due to its photoperiod sensitivity (its flowering is accelerated only in short days). For photoperiod sensitivity rice, delay flowering usually occurs when photoperiods is less or more than 12-15 hours at panicle initiation phase because short-day plants flower when night length exceeds a critical dark period to induced panicle formation. Thus, photoperiod sensitivity cultivars could be grown in off-season, however, its flowering will be delayed causing more withered seeds and immature kernel (underdeveloped seed) with lower yield that similar to this experiment results (Saranukromthai, 1977; Ikeda, 1985; Wangcharoen et al, 2015; Rice Department, 2016a; Vanavichit et al., 2018; Sarutayophat et al., 2020). On the contrary, PT 1 is a non-photoperiod sensitive cultivar (Rice Department, 2016b) which could be grown year-round in several environmental conditions particularly in irrigated areas (Sreethong et al., 2018). Therefore, the more sensitivity of KDML 105 yield to drought might be contributed to its falling grain under drought, delay flowering, and it's out-growing season in this experiment.

4.3.6 Correlation analysis between physiological traits and dry matter of rice

Correlation analysis between physiological processes and DM of PT 1 in C soil was described in Table 4.3. Positive correlations were obtained between DM and LWP_{pd}, g_s, A, SPAD value, and Fv/Fm ratio at all growth stages. LWP_{pd} had the highest correlation with DM (0.961**) at seedling stage while SPAD value had the highest correlation with DM (0.948**) at tillering stage. The g_s had the highest correlation with DM (0.954**) at flowering stage.

Table 4.3 Correlation coefficient between physiological traits and dry matter of PT 1 at seedling, tillering, and flowering stages in C soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	DM
Seedling	LWP_{pd}	0.808**	0.860**	0.924**	0.850**	0.961**
	A		0.855**	0.876**	0.855**	0.922**
	g_s			0.920**	0.801**	0.877**
	SPAD				0.872**	0.953**
	Fv/Fm ratio					0.888**
Tillering	LWP_{pd}	0.880**	0.873**	0.862**	0.891**	0.860**
	A		0.986**	0.913**	0.873**	0.914**
	g_s			0.896**	0.837**	0.905**
	SPAD				0.903**	0.948**
	Fv/Fm ratio					0.912**
Flowering	LWP_{pd}	0.912**	0.871**	0.867**	0.928**	0.884**
	A		0.946**	0.919**	0.908**	0.888**
	g_s			0.852**	0.899**	0.954**
	SPAD				0.811**	0.714**
	Fv/Fm ratio					0.951**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; DM, dry matter.

** significant differences at ≤0.01.

Similarly, the correlation coefficient between physiological processes and DM of PT 1 in SCL soil was described in Table 4.4. Positive correlations were obtained between DM and LWP_{pd}, g_s, A, SPAD value, and Fv/Fm ratio during the experiment. SPAD value had the highest correlation with DM at 0.977** at seedling stage while A had the highest correlation (0.960**) with DM at tillering stage. Fv/Fm ratio had the highest correlation (0.974**) with DM at flowering stage.

Table 4.4 Correlation coefficient between physiological traits and dry matter of PT 1 at seedling, tillering, and flowering stages in SCL soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	DM
Seedling	LWP_{pd}	0.981**	0.916**	0.924**	0.824**	0.941**
	A		0.918**	0.932**	0.859**	0.956**
	g_s			0.933**	0.819**	0.942**
	SPAD				0.815**	0.977**
	Fv/Fm ratio					0.869**
Tillering	LWP_{pd}	0.971**	0.959**	0.918**	0.884**	0.927**
	A		0.964**	0.920**	0.883**	0.960**
	g_s			0.875**	0.848**	0.937**
	SPAD				0.930**	0.925**
	Fv/Fm ratio					0.940**
Flowering	LWP_{pd}	0.907**	0.909**	0.898**	0.925**	0.933**
	A		0.978**	0.879**	0.934**	0.872**
	g_s			0.879**	0.934**	0.876**
	SPAD				0.905**	0.915**
	Fv/Fm ratio					0.974**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; DM, dry matter.

** significant differences at ≤0.01.

Correlation analysis between physiological processes and DM of KDML 105 in C soil was described in Table 4.5. Positive correlations were obtained between DM and LWP_{pd}, g_s, A, SPAD value, and Fv/Fm ratio at all growth stages. A had the highest correlation (0.976**) with DM at seedling stage while SPAD value had the highest correlation (0.975**) with DM at tillering stage. The g_s had the highest correlation (0.946**) with DM at flowering stage.

Table 4.5 Correlation coefficients between physiological traits and dry matter of KDML 105 at seedling, tillering, and flowering stages in C soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	DM
Seedling	LWP_{pd}	0.938**	0.895**	0.919**	0.898**	0.950**
	A		0.953**	0.887**	0.948**	0.976**
	g_s			0.881**	0.922**	0.945**
	SPAD				0.839**	0.859**
	Fv/Fm ratio					0.948**
Tillering	LWP_{pd}	0.936**	0.924**	0.951**	0.879**	0.973**
	A		0.911**	0.917**	0.827**	0.931**
	g_s			0.912**	0.739**	0.924**
	SPAD				0.880**	0.975**
	Fv/Fm ratio					0.919**
Flowering	LWP_{pd}	0.905**	0.923**	0.706**	0.855**	0.883**
	A		0.931**	0.750**	0.854**	0.937**
	g_s			0.710**	0.845**	0.946**
	SPAD				0.712**	0.668*
	Fv/Fm ratio					0.878**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; DM, dry matter.

*, ** significant differences at ≤0.05 and 0.01 respectively.

Correlation analysis between physiological processes and DM of KDML 105 in SCL soil was described in Table 4.6. Positive correlations were obtained between DM and LWP_{pd}, g_s, A, SPAD value, Fv/Fm ratio at all growth stages. LWP_{pd} had the highest correlation (0.962**) with DM at seedling stage while A had the highest correlation (0.944**) with DM at tillering stage. Fv/Fm ratio had the highest correlation (0.946**) with DM at flowering stage.

Table 4.6 Correlation coefficient between physiological traits and dry matter of KDML 105 at seedling, tillering, and flowering stages in SCL soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	DM
Seedling	LWP_{pd}	0.950**	0.954**	0.839**	0.927**	0.962**
	A		0.936**	0.777**	0.928**	0.952**
	g_s			0.803**	0.943**	0.923**
	SPAD				0.816**	0.715**
	Fv/Fm ratio					0.911**
Tillering	LWP_{pd}	0.834**	0.756**	0.853**	0.853**	0.737**
	A		0.933**	0.931**	0.955**	0.944**
	g_s			0.930**	0.912**	0.940**
	SPAD				0.927**	0.916**
	Fv/Fm ratio					0.930**
Flowering	LWP_{pd}	0.936**	0.915**	0.883**	0.921**	0.914**
	A		0.979**	0.880**	0.959**	0.939**
	g_s			0.857**	0.951**	0.934**
	SPAD				0.927**	0.894**
	Fv/Fm ratio					0.946**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; DM, dry matter.

** significant differences at ≤0.01.

4.3.7 Correlation analysis between physiological traits and grain yield of rice in two textured soils

Correlation analysis between physiological processes and GY of PT 1 were described in Table 4.7 and Table 4.8. Positive correlations were obtained between GY and all physiological traits at all growth periods in both soils. For PT 1 in C soil, the g_s had the highest correlation with GY at seedling and tillering stages (0.912** and 0.971**, respectively) while A had the highest correlation (0.968**) at flowering stage (Table 4.7). Besides, PT 1 in SCL soil, the A had the highest correlation with GY at seedling, tillering, and flowering stages (0.938**, 0.919**, and 0.968**, respectively) (Table 4.8).

Table 4.7 Correlation coefficient between physiological traits and grain yield of PT 1 in C soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	GY
Seedling	LWP_{pd}	0.808**	0.860**	0.924**	0.850**	0.790**
	A		0.855**	0.876**	0.855**	0.768**
	g_s			0.920**	0.801**	0.912**
	SPAD				0.872**	0.873**
	Fv/Fm ratio					0.622*
Tillering	LWP_{pd}	0.880**	0.873**	0.862**	0.891**	0.882**
	A		0.986**	0.913**	0.873**	0.950**
	g_s			0.896**	0.837**	0.971**
	SPAD				0.903**	0.851**
	Fv/Fm ratio					0.812**
Flowering	LWP_{pd}	0.912**	0.871**	0.867**	0.928**	0.890**
	A		0.946**	0.919**	0.908**	0.968**
	g_s			0.852**	0.899**	0.938**
	SPAD				0.811**	0.934**
	Fv/Fm ratio					0.910**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; GY, grain yield.

*, ** significant differences at ≤0.05 and 0.01 respectively.

Table 4.8 Correlation coefficient between physiological traits and grain yield of PT 1 in SCL soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	GY
Seedling	LWP_{pd}	0.981**	0.916**	0.924**	0.824**	0.936**
	A		0.918**	0.932**	0.859**	0.938**
	g_s			0.933**	0.819**	0.928**
	SPAD				0.815**	0.913**
	Fv/Fm ratio					0.903**
Tillering	LWP_{pd}	0.971**	0.959**	0.918**	0.884**	0.876**
	A		0.964**	0.920**	0.883**	0.919**
	g_s			0.875**	0.848**	0.846**
	SPAD				0.930**	0.863**
	Fv/Fm ratio					0.880**
Flowering	LWP_{pd}	0.907**	0.909**	0.898**	0.925**	0.890**
	A		0.978**	0.879**	0.934**	0.968**
	g_s			0.879**	0.934**	0.949**
	SPAD				0.905**	0.860**
	Fv/Fm ratio					0.915**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; GY, grain yield.

** significant differences at ≤0.01.

In KDML 105 cultivar, positive correlations were obtained between GY and all physiological traits at all growth periods in both soils. The g_s had the highest correlation with GY at seedling and flowering stages (0.889** and 0.947**, respectively) while LWP_{pd} had the highest correlation (0.865**) at tillering stages in C soil (Table 4.9). In SCL soil, Fv/Fm ratio had the highest correlation with GY at seedling and tillering stages (0.968** and 0.926**, respectively) while A had the highest correlation at flowering stage (0.942**) (Table 4.10).

Table 4.9 Correlation coefficient between physiological traits and grain yield of KDML 105 in C soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	GY
Seedling	LWP_{pd}	0.935**	0.895**	0.919**	0.898**	0.818**
	A		0.953**	0.887**	0.948**	0.847**
	g_s			0.881**	0.922**	0.889**
	SPAD				0.839**	0.785**
	Fv/Fm ratio					0.838**
Tillering	LWP_{pd}	0.936**	0.924**	0.951**	0.879**	0.865**
	A		0.911**	0.917**	0.827**	0.745**
	g_s			0.912**	0.739**	0.850**
	SPAD				0.880**	0.763**
	Fv/Fm ratio					0.602**
Flowering	LWP_{pd}	0.905**	0.923**	0.706**	0.855**	0.945**
	A		0.931**	0.750**	0.854**	0.926**
	g_s			0.710**	0.845**	0.947**
	SPAD				0.712**	0.688**
	Fv/Fm ratio					0.862**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; GY, grain yield.

** significant differences at ≤0.01.

Table 4.10 Correlation coefficient between physiological traits and grain yield of KDML 105 in SCL soil.

Rice stages	Physiological traits[1]	A	g_s	SPAD	Fv/Fm ratio	GY
Seedling	LWP_{pd}	0.950**	0.54**	0.839**	0.927**	0.920**
	A		0.936**	0.777**	0.928**	0.928**
	g_s			0.803**	0.943**	0.935**
	SPAD				0.816**	0.764**
	Fv/Fm ratio					0.968**
Tillering	LWP_{pd}	0.834**	0.756**	0.853**	0.853**	0.862**
	A		0.933**	0.931**	0.955**	0.890**
	g_s			0.930**	0.912**	0.917**
	SPAD				0.927**	0.921**
	Fv/Fm ratio					0.926**
Flowering	LWP_{pd}	0.936**	0.915**	0.883**	0.921**	0.913**
	A		0.979**	0.880**	0.959**	0.942**
	g_s			0.857**	0.951**	0.883**
	SPAD				0.927**	0.881**
	Fv/Fm ratio					0.937**

[1]LWP_{pd}, predawn leaf water potential; A, net photosynthesis rate; g_s, stomatal conductance; GY, grain yield.

** significant differences at ≤0.01.

From the correlation analysis, the overall results indicated that the positive correlations were obtained between DY, GY, and all physiological traits. Among physiological traits, LWP_{pd} and A consistently had the highest positive correlations with GY and DM in both cultivars and both soils. Similar to the research of Bielorai (1973) and Hsiao (1993) who reported that physiological traits such as LWP_{pd}, A, and g_s were more sensitive to soil moisture content than other traits. Yang et al. (2019) also found that GY had significantly positive correlated with A and g_s under stress. Corresponded to Jongdee, Fukai, and Cooper (2002) who suggested that maintaining of high leaf water potential helps to minimize the negative effects in water deficit on spikelet sterility and GY. Moreover, LWP and photosynthesis activities are physiological traits that are commonly used to study plant drought tolerant and was less influence due to drought period and stress level especially the LWP. Thus, LWP is the most important trait for studying plant-water status and drought tolerant genotypes.

4.3.8 Determination of critical soil moisture content

Critical soil moisture content (CMC) is the soil moisture content at the moment of the first reduction in stomata closure or growth mechanism (Jong Van Uer, 1997). It is the point of the first reduction in plant water consumption which resulting in plant growth and yield reduction. Thus, the plants should be re-watering again before soil moisture content is lower than critical point otherwise rice yield will be affected. CMC could be identified from the correlation analysis between the physiological traits and DM (Table 4.3, 4.4, 4.5, and 4.6). All physiological traits had highly correlated with DM and GY of two cultivars in both soils however, LWP_{pd} often had the highest correlation with DM and GY and had less influence from other variables. LWP_{pd} is a represented for the mean soil moisture potential next to the roots that is closely correlated to transpiration rate and whole plant water potential (Améglio et al., 1999). It can repletely observe throughout the rice growth cycle with a simple method that do not damage the plant samples as much as other growth parameters including DM, yield, and yield components. Therefore, it was chosen to evaluate the CMC in both rice cultivars in this research. However, Dinh et al. (2019) suggested that photosynthetic parameters could be used to determine the time to re-irrigate under drought due to critical soil moisture content at 10% VWC resulting in photosynthetic disorders that affected sugarcane growth.

The linear regressions between LWP_{pd} and soil moisture contents in each cultivar were performed. The critical points of soil moisture (CMC) were determined from the intersection of two linear regression lines from the correlation (Figure 4.16, 4.17, 4.18, 4.19, 4.20, and 4.21). From the evaluation, the CMC of PT 1 were 60% AWHC in C and SCL soils at seedling stage while in KDML 105 were 60% AWHC in C soil and 70% AWHC in SCL soil (Figure 4.16 and 4.17). At tillering stage, the CMC in PT 1 and KDML 105 should not below 70% AWHC in C and SCL soils (Figure 4.18 and 4.19). The CMC in PT 1 should not below 70% AWHC in C and SCL soils at flowering stage while KDML 105 it was 60% AWHC in C soil and should not below 70% AWHC in SCL soil (Figure 4.20 and 4.21). If the soil moisture content dramatically decreased from 70 to 20% AWHC, the CMC should not below 70% AWHC in each soil texture and might be higher than 70% AWHC.

These results agreed with Ghosh and Singh (2010) who found that 40 kPa soil moisture tension or 42.8% SMC was considered to be the CMC for optimum grain yield and maximum water productivity of aerobic rice Indian cultivation. Similar to Yang et al. (2015) who concluded that the appropriate soil volumetric moisture content at 43% was the CMC for soil respiration in paddy field with water-saving irrigation at early tillering to milk stages of rice. In contrast, Suralta et al. (2010) found that soil should be maintained at 10% SMC in rice seedling because this point was close to the CMC in legumes and cereals (8% SMC or -0.28 MPa).

Doorenbos et al. (1980) described that CMC is a function of plant sensibility to drought and evapotranspiration demand. CMC could be used to determine the scheduling irrigation and arranging irrigation in many plant species. Martínez-Gimeno et al. (2020) also suggested that determination of the CMC is a useful tool for scheduling irrigation, when applied in mandarin orchard with the sensor-based strategy resulted in water saving by 26% and increased the crop water productivity by 33%. Machikowa et al. (2019) also reported that the CMC in various soil types is very useful for precision irrigation management in cassava. Additionally, CMC is an important for monitoring crop to investigate drought response and estimating crop productivity in a certain environment. CMC could be applied with irrigation systems to schedule the watering level in rice cultivation such as saturated soil culture (SSC), alternate wetting and drying (AWD), aerobic rice, and system of rice intensification (SRI) (Singh et al., 2013). In particular, alternate wetting and drying (AWD) irrigation is one of the techniques that can use the CMC to determine the watering level in each soil textures and rice cultivars for more accurate irrigation control than the conventional methods.

In this experiment, CMC was different among rice growth stage, rice cultivars, and soil texture. Differences in cultivar and growth stage resulted in different the CMC because it had a different morphology and physiology such as leaf elongation, root elongation and root expansion. Each growth stages, rice requires different amount of water to maintain the optimal growth and yield. In addition, soil texture is also the important factor that affect CMC because each soil texture contains a different level of soil moisture content i.e., fine texture soils have more specific surface area to hold water which resulted in high AWHC and high CMC (Machikowa et al., 2019).

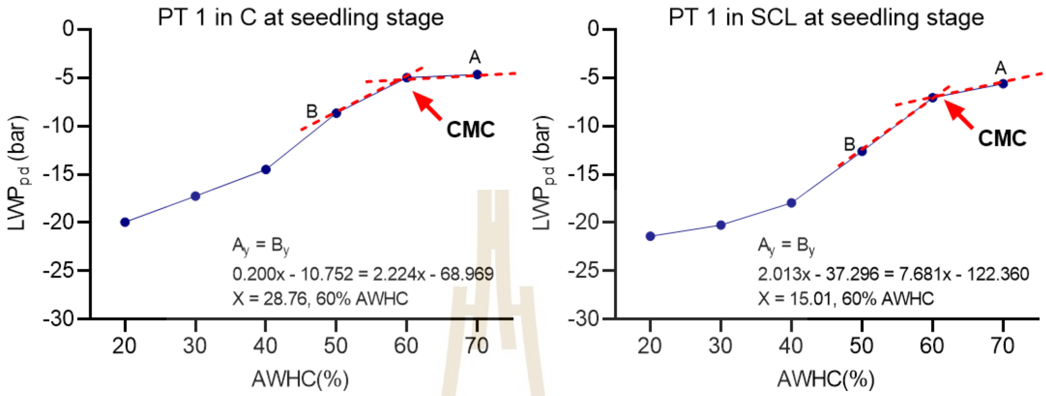


Figure 4.16 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of PT 1 at seedling stage in C and SCL soils.

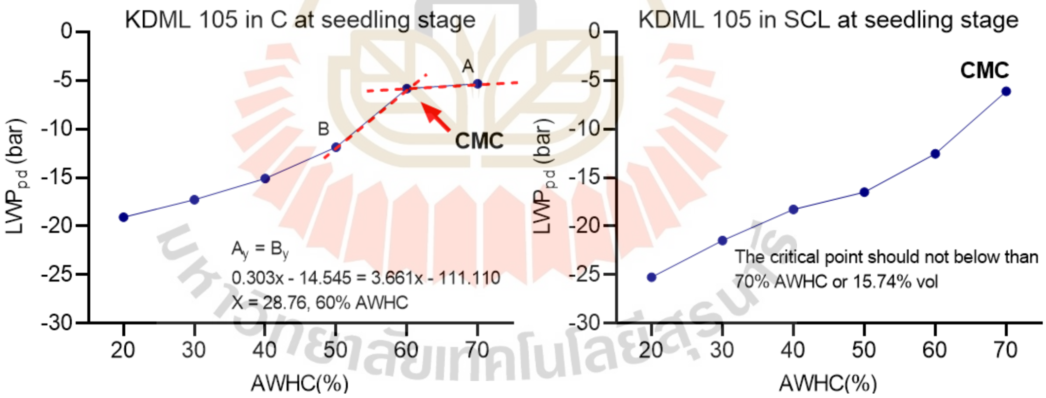


Figure 4.17 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of KDML 105 at seedling stage in C and SCL soils.

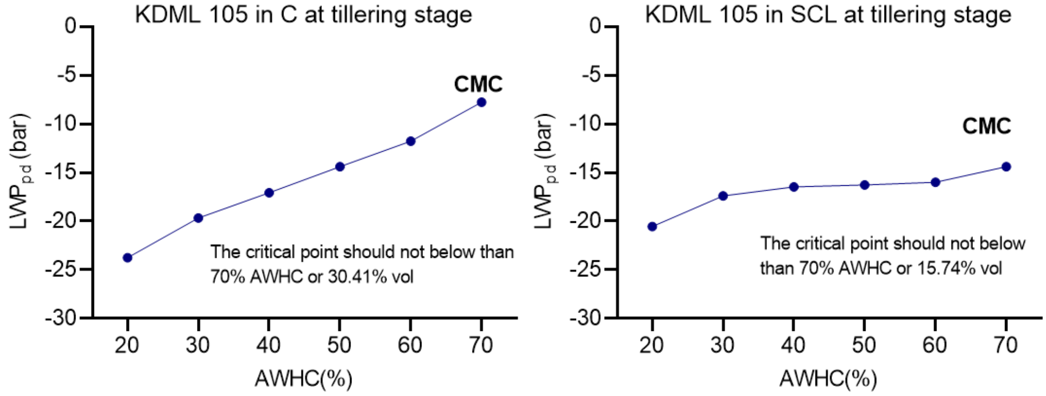


Figure 4.18 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of PT 1 at tillering stage in C and SCL soils.

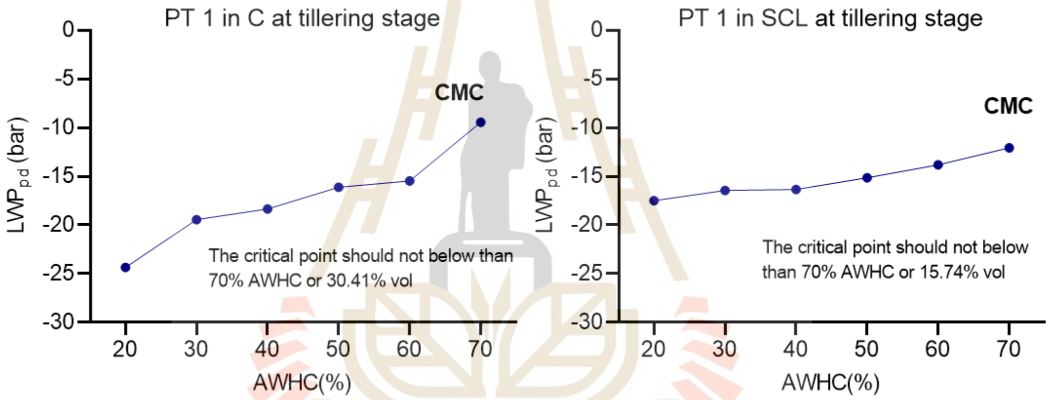


Figure 4.19 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of KDML 105 at tillering stage in C and SCL soils.

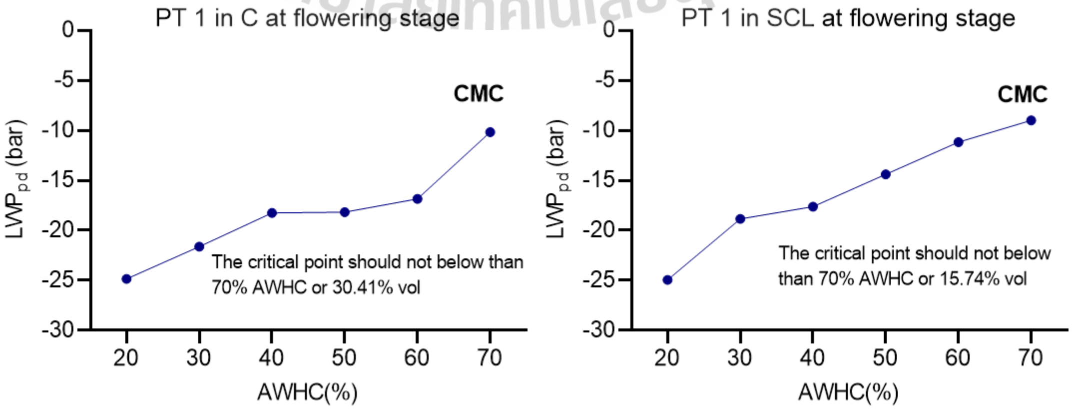


Figure 4.20 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of PT 1 at flowering stage in C and SCL soils.

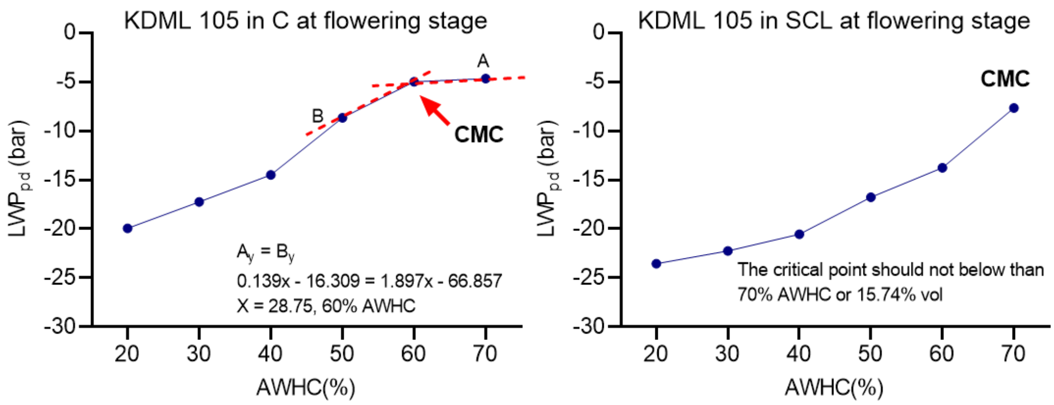


Figure 4.21 The critical soil moisture content from the correlation between LWP_{pd} and soil moisture content of KDML 105 at flowering stage in C and SCL soils.

4.4 Conclusion

Morphological and physiological traits of both rice cultivars and soils significantly decreased when soil moisture levels decreased at all growth stages while leaf rolling score increased. Yield and yield components also decreased when soil moisture levels decreased particularly grain yield. Drought had negative effect on plant water absorption which led to water potential and leaf gas exchange reduction resulting in morphological changes and yield reduction. All physiological traits were positively correlated with dry matter and grain yield particularly LWP_{pd} and A. Thus, LWP_{pd} and A might be the great target for plant breeder in improving rice drought-tolerant in breeding program due to it had the strong influence at all growth stages. However, LWP_{pd} was chosen to evaluate the CMC as it consistently had high correlation with dry matter. The CMC of both rice cultivars in each soil were determined from the regression analysis between LWP_{pd} and soil moisture contents. The results found that CMC of PT 1 were 60% AWHC in C and SCL soils at seedling stage while CMC in KDML 105 were 60 and 70% AWHC in C and SCL soils, respectively. At tillering stage, CMC in PT 1 and KDML 105 should not below 70% AWHC in C and SCL soils. However, the CMC at flowering stage in PT 1 should not below 70% AWHC in C and SCL soils, while in KDML 105 was 60 and 70% AWHC in C and SCL soils respectively. Under drought, rice response varied between cultivars, growth stages, and soil textures. PT 1 cultivars was more sensitive to drought than KDML 105 cultivar particularly in flowering stage. These results research also suggested that LWP could be used for studying plant-water status and evaluated drought tolerant characters because it had the highest correlation with grain yield, less influence from other variables, and it can be measured at all growth stages without damaging the whole plant. The CMC values from this study can be used as the watering index in particular irrigation systems such as alternate wetting and drying (AWD) and system of rice intensification (SRI) for the precision water application in each soil texture and rice cultivar.

4.5 References

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CHAPTER V
CONCLUSION

A series of two experiments was conducted to study the responses of two rice cultivars (KDML 105 and PT 1) to drought condition. The first experiment was conducted under a hydroponic system to study the morphological and physiological traits, biochemical process, yield, and yield components of rice under water stress conditions at seedling, tillering, and flowering stages. The results showed that morphological and physiological traits were significantly decreased throughout the experiment while free proline and spermidine contents increased under stress both cultivars. All traits under the stress of PT 1 decreased more than those of KDML 105 except plant height and free proline content. Yield and yield components were reduced particularly in grain yield of PT 1 by more than 40%. Positive correlations were obtained between grain yield and all physiological traits, particularly in LWP_{pd}.

The second experiment was conducted under greenhouse conditions to study the rice response to drought stress and to identify the CMC of rice in two soils. The morphological and physiological traits were evaluated when the soil moisture content reached to the indicated levels of 20, 30, 40, 50, 60, and 70% AWHC at seedling, tillering, and flowering stages. The results showed that morphological and physiological traits significantly reduced when soil moisture levels decreased at all growth stages, while leaf rolling score increased in both cultivars and soils. Yield and yield components also decreased when soil moisture levels decreased. All physiological traits positively correlated with dry matter and grain yield in both cultivars particularly in LWP_{pd}. LWP_{pd} was chosen to use for CMC evaluation because of its high correlations with dry matter, low influences from other variables, and can be repletely observed under drought. The CMC were determined from the regression analysis between LWP_{pd} and soil moisture. The results found that CMC of PT 1 were 60% AWHC in C and SCLsoils at seedling stage while CMC in KDML 105 were 60% AWHC and should not below70% AWHC in C and SCL soils, respectively. At tillering stage, CMC in PT 1 and KDML 105 should not below 70% AWHC in C and SCL soils. However, the CMC at flowering stage in PT 1 should not below 70% AWHC in C and SCL soils, while in KDML 105 was 60% AWHC in C soil and should not below 70% AWHC in SCL soil.

In this experiment, the magnitudes of morphological and physiological response depended on rice cultivar, growth stages, and soil textures. This result indicated that LWP and photosynthetic rate might be the great target for plant breeder in improving drought-tolerant character in rice breeding program due to it had the strong influence on rice yield and dry biomass at all growth stages. It also could be indicating the plant water status, plant-water relations, and CMC level. Moreover, the CMC is an important information to determine the watering index more accurately in each soil textures and rice cultivar by applied with irrigation systems such as AWD and SRI techniques for reduce cost production and reduce crop water use.

BIOGRAPHY

Miss Saranyapath Pairintra was born on October 26, 1996 at Khon Kaen, Thailand. She graduated with Senior High School from Khon Kaen Wittayayon School, Khon Kaen and started the Bachelor Degree in Crop Production Technology at Suranaree University of Technology in 2015. She graduated in Semester 3/2018.

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