Investigation of Alternate Wetting and Drying Irrigation Practice for Climate-Smart Water Management in Paddy Rice Fields

「水田における気候変動に対応した水管理のための間断灌漑に関する研究」

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Agricultural and Environmental Engineering
United Graduate School of Agricultural Science
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学位論文要旨

Investigation of Alternate Wetting and Drying Irrigation Practice for Climate-Smart Water Management in Paddy Rice Fields

水田における気候変動に対応した水管理のための間断灌漑に関する研究

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Water is an integral component of food security and a valuable resource for paddy cultivation, primarily practiced using traditional flooding conditions. Paddy rice cultivation is expanding in Sub-Saharan Africa, East Africa in particular. However, the expansion is being affected by climate change events: droughts, floods, and other intensified hazards. These contribute to reduced rice yields and changes in traditional seasons, leaving the region in a vicious cycle of food insecurity and malnutrition. Despite the region's enormous agricultural potential, the region largely depends on rice imports (> 500,000 tons annually) from Asia. In this study, literature synthesis was conducted to assess the potential of AWD technology in East Africa. Research questions, including why AWD is less practiced in the region were formulated, to (i) unveil critical gaps and core issues on paddy rice production systems, water management and food security in four EA countries (Uganda, Kenya, Tanzania, and Ethiopia) and (ii) examine future trajectories to improve paddy rice production in the region for building stable food security under threats of climate change. The literature search was performed from electronic databases on key scientific papers, technical reports, and data on food insecurity, paddy rice production systems, water management, and government policies. This synthesis shows that water scarcity due to decreasing precipitation is a major threat to paddy rice production, while food insecurity is linked to low agricultural productivity. The region has registered increased rice production since 2000, attributed to a slight expansion in irrigated areas. Climate-smart agricultural technologies, including alternate wetting and drying (AWD) and system of rice intensification SRI are being practiced at the micro-research level promising for improving yields, though is little is known about AWD technology among farmers.

The study evaluated the effect of AWD regimes on paddy rice cultivation in phytotron from Feb/2021 to March/2022 at Tokyo University of Agriculture and Technology (TUAT), Japan. Three AWD regimes—AWD5, AWD10 & AWD15 as treatments, were defined when the water level in observation tubes dropped to -5, -10 and -15 cm below the ground surface, and continuous flooding (CF) as control—when water ponded water disappeared from the ground surface. Rice variety Ikuhikari, a short Japanese widely grown rice cultivar, was directly seeded during the pot rice cultivations. Agronomic parameters and soil hydrological conditions were measured, including crop growth, tillers, yield components, biomass, harvest index, and pressure head. The results showed no significant difference (5%) between irrigation treatments regarding yield components, including tiller and number of panicles, harvest index and water productivity. Any water stress due to different water management at panicle and grain formation affected crop growth. AWD regimes had high water productivity and improved irrigation water saving by up to 36 %. Hydrological conditions during crop growth indicate the low-pressure head among the water regimes even in CF. Similarly, the pressured heads varied with the crop growth stage as observed towards the end of crop development to reproductive stages. However, the changes in pressured head were proportional to water regimes although the lowest pressure head of -900 cm was observed in AWD15. The low pressure in AWD regimes was attributed to high transpiration and soil drying.

The HYDRUS-1D model was applied to examine the influence of different water management strategies (CF and AWD regimes) on water flow and soil water balance components in directly seeded paddy rice at pot scale. Initially the potential ET was estimated using the Penman-Monteith (PM) equation and was found inadequate for the closed system with pot rice cultivation due to low ET values. Adjusting potential ET for the pot rice conditions was done by obtaining the correction factor (Cf) based on the relationship of the ground surface area of the phytotron over the surface area of pots, the number of pots and crop density. The Cf was used for adjusting ET in HYDRUS-1D that gave ten times higher ET than the PM-FAO method. The high ET is attributed to the high potential transpiration component of ET. The simulated and observed pressured heads varied quantitively—not straightforward. Water balance and hydrological processes in pot conditions differ from field conditions.

We further evaluated the influence of deficit irrigation scenarios on the root water uptake of paddy rice using HYDRUS-1D model. Three deficit irrigation scenarios were defined by 80, 60 and 40 % the total water applied (TWA) of CF while maintaining irrigation frequency thus 80TWA, 60TWA, and 40TWA. The simulated RWU accounted for 75, 83, 87 and 88 % of TWA corresponding to CF, 80TWA, 60TWA, and 40TWA. HYDRUS-1D is an important tool for simulating deficit irrigation scenarios and irrigation planning. Future research should consider carrying out pilot AWD technology and deficit irrigation scenarios in paddy rice field condition in East Africa—Uganda, to obtain evidenced data for promoting AWD technology in the region.

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……. "For the Lord raises the poor from the dust and lifts the needy from the ash heap, seating them among the princes and nobles, bestowing on them a throne of honour'. 1 Sam. 2:8a, and a man's gift makes room for him and ushers him into greatness. Proverbs 18:16.... Paraphrased".

Dedication

To my dear Wife: Justine NAMUZUNGU BWIRE and children–Ephraim OPIO BWIRE, Stephie ADONGO BWIRE and Misha MUHONGO BWIRE

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Abbreviations, Glossary and Symbols

θ	Water content
θ_r	Residual Water Content
θ_s	Saturated Water content
Δw	Change in ponded water.
AIC	Akaike information criterion
AWD	Alternate Wetting and Drying
CF	Continuous Flooding
CH4	Methane gas
EA	East Africa
EAGC	Eastern African Grain Council
Ep	Potential Evaporation
ET	Evapotranspiration
ETc	Crop water requirements
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FWL	Field water level
GDP	Gross Domestic Product
GHA	Great Horn of Africa
GHG	Greenhouse gas emissions
GWP	Global warming potential
HS	Sensible Heat
IoT	Internet of Thing
IRRI	International Rice Research Institute
ITCZ	Inter-Tropical Convergence Zone
IWMI	International Water Management Institute
Ks	Saturated hydraulic conductivity
LAI	Leaf Area Index
LE	Latent heat
MAE	Mean Absolute error.
N2O	Nitrous Oxide
NR	Net Radiation
OBF	Over-bund flow
PAR	Photosynthetically active radiation.
PI	Puddling Index
RMSE	Root mean square error.
RWU	Root water uptake
Se	Relative Saturation
SOC	Soil organic carbon
SSA	Sub-Saharan Africa
SWC	Soil Water Conservation Measures
SWP	Soil Water potential
Tp	Potential Transpiration
TWA	Total water applied.
UN	United Nations
USDA	United States Department of Agriculture
VP	Vertical percolation
VW	Virtual Water
WF	Water Footprint
WL	Water level

Chap. 1: Introduction

1.1 Background

1.1.1 Global Water Issues, Rice Production and Food Security

Water stress is an increasingly common global challenge as climate change affects water availability in many regions inhibiting livelihoods and environmental functions, especially related to agriculture crop production and food security (Misra, 2014; Young et al., 2021; Sidle et al., 2023). Water and food are essential for human survival, and there is an increasing demand for food with the looming water crisis calling for innovative technologies (Parthasarathi et al., 2012). Water can be a matter of life and death, depending on how it is managed, as well as an instrument for economic growth, poverty alleviation, and increased crop production (UN-Water-Africa, 2000).

Food security may be defined as food availability to meet one's nutritional requirements (Karen, 2014). Broadly it is whether the population has monetary and non-monetary resources to allow everyone have access to adequate quantities and quality of food (Schmidhuber and Tubiello, 2007). Globally, the role of water in ensuring food security and well-being has been underappreciated, and food security is critical to the Sustainable Development Goals and government policies in East Africa (EA) and Sub-Saharan Africa (SSA). Additionally, water scarcity is becoming a global concern and the number of people living in areas with insufficient water is increasing in the developed, developing, and underdeveloped parts of the world (World Economic Forum, 2020).

Rice is a major crop grown primarily in paddy fields where eco-hydrological processes, impacted by water regimes, are critical controls for irrigation management. While rice is a global staple crop essential for food security (Djaman et al., 2020; Pourgholam et al. 2020), the future of rice production is compromised by its greater susceptibility to drought stress than other cereal crops. Because drought stress is predicted to increase with global warming in many areas (Delong and Wieland, 2017), irrigation supplies and costs may restrict paddy rice production, in some areas lending it unpracticable. Likewise, extreme weather events, such as heavy rains attributed to climate change, cause huge damage and losses to paddy rice production.

Paddy production is declining (Table1), and there is a concern that global warming may affect water availability and management for future paddy cultivation (Peng et al., 2004; Saud et al., 2022). Increasing water shortages are affecting four billion people globally (Mekonnen and Hoekstra, 2016) and, by 2025, rice production is predicted to experience a 20% water deficit (Tuong and Bouman, 2003). Although rice contributes significantly to ensuring global food security, traditional continuous flooding (CF) in paddy rice production requires more water than other cereal crops (Pimentel et al., 2004). Furthermore, CF is a weed management strategy that maintains anaerobic conditions in the paddy-rice rhizosphere by maintaining anoxic conditions in the soil due to the long duration of ponded water (Bwire et al., 2022b). Rice cultivation requires much water, up to 2500 L for 1 kg of rice produced, compared to other crops (Carrijo et al., 2017).

Table 1. 1: Top 15 rice (milled) producing countries worldwide for the past five years; 2019-2023. Source: USDA.

Country	2018/19	2019/20	2020/21	2021/22	2022/23
China	148,490	146,730	148,300	148,990	145,946
India	116,484	118,870	124,368	129,471	132,000
Bangladesh	34,909	35,850	34,600	35,850	35,850
Indonesia	34,200	34,700	34,500	34,400	34,600
Vietnam	27,344	27,100	27,381	26,769	27,000
Thailand	20,340	17,655	18,863	19,878	20,200
Burma	13,200	12,650	12,600	12,352	12,500
Philippines	11,732	11,927	12,416	12,540	12,411
Japan	7,657	7,611	7,570	7,636	7,450
Brazil	7,140	7,602	8,001	7,337	6,936
Pakistan	7,202	7,206	8,420	9,323	6,600
Cambodia	5,742	5,740	5,739	5,771	5,933
Nigeria	5,294	5,314	5,148	5,255	5,040
Korea South	3,868	3,744	3,507	3,882	3,764
Nepal	3,736	3,697	3,744	3,417	3,654
Others	43,780	46,667	46,939	44,898	44,854
Subtotal	491,118	493,063	502,096	507,769	504,738
World Total	498,225	498,940	509,320	513,852	509,830

This research focused on water management, paddy rice cultivation and agronomic strategies that reduce water use without affecting rice yields to support growing populations, with attention to minimal weed growth. Several water-saving irrigation techniques have been developed for paddy rice cultivation. These include direct (dry) sowing, intermittent dry spells (Feng, 2007), partial root drying, alternating wetting, and drying irrigation (AWD) irrigation (Lampayan et al., 2015b), and combination of shallow water depth with wetness and dryness

(Mao, 2001). These irrigation and water management methods aim to improve water use efficiency.

1.1.2 Paddy Rice Cultivation Systems and Hydrological Conditions

Rice paddy is predominantly grown in wet conditions, whose eco-hydrological characteristics are impacted by water regimes. The term "paddy" is derived from the Malay word padi, meaning "rice plant", originated from Proto-Austronesian. The concept of paddy fields is generally referred to as a paddy rice farm, mainly in flooded conditions (Watanabe, 2018). Paddy fields are designed with irrigation and drainage canals. Designing an irrigation scheme is highly complex, combining a myriad of technical, economic, agronomic, and social factors. However, the main task is to create a layout which enhances availability and equitable water distribution among farmers. The design of rice paddy fields should aim at agricultural water management for effective water use, although 60 % of all irrigated land globally requires improvement (Suzuki, 1994). In addition, it involves intensive farmland consolidation to enhance regular fields in conjunction with straight segments of ditches and roads (Odhiambo and Murty, 1996). Likewise, inappropriate management and unfair water distribution due to poor field design are reasons why irrigation systems are not exhibiting their full capabilities (Suzuki, 1994).

Depending on the hydrology of the rice field, the paddy rice environment can be classified into irrigated lowland rice, rainfed lowland rice, and flood-prone rice (Table 2.1). Irrigated lowland rice is grown in bunded fields with irrigation to produce one or more crops per year, and farmers usually maintain 5–10 cm of flooded water in the field (Bouman et al., 2007). Rainfed lowland rice is grown in bunded fields flooded with rainwater for at least part of the cropping season. In both cases, fields are puddled with rice transplanted to establish crops. In flood-prone areas, paddy fields periodically suffer from excess water and uncontrolled deep flooding (Maclean et al., 2002; Bounman et al., 2007).

Table 1. 2: Rice Cultivation environment, climate and major rice growing region. Source; Gadel et al., 201; Khus et al., 1984

S/N	Major Categories	Sub-categories	Climate Description	Major Regions/countries
1	Irrigated	With favorable temperature. With low-temperature, tropical zone. With low temperature, temperate zone	Warm to hot—tropics (rice all seasons) and subtropics (double crop summer rice)	Indonesia, Sri Lanka, Vietnam, the Philippines, south-eastern India, south-ern China, Bangladesh
			Warm—tropics (higher altitudes) and subtropics (sole rice after winter crop)	South Asia hills, Indo-Gangetic Plain, central China
			Temperate (summer rice after winter fallow, warm and humid)	Japan, Korean peninsula, north-eastern China, southern Brazil, southern USA

			Temperate (summer rice after winter fallow, hot and dry)	Egypt, Iran, Italy, Spain, California (USA), Peru, south-eastern Australia
2	Rainfed Lowland	RFS, favorable RFS, drought prone. RFS, drought-and submergence-prone. RFS, submergence-prone RFM deep, waterlogged	Tropics	Cambodia, North-East Thailand, eastern India, Indonesia, Myanmar, Nigeria
3	Upland	Favorable upland with LGS. Favorable upland with SGS. Unfavorable upland with LGS. Unfavorable upland with SGS.	Tropics	South Asia, South-East Asia, Brazilian Cerrado, western Africa, East Africa; Uganda
4	Deep Water	Deep water Very deep water	Tropics	River deltas of South Asia and South-East Asia, Mali
5	Tidal wetlands	TW with perennial fresh water. TW with seasonal or perennial saline water. TW with acid sulfate soils. TW with peat soils	Tropics	Vast areas near seacoasts and inland estuaries in Indonesia (Sumatra and Kalimantan), Vietnam and smaller areas in India, Bangladesh, and Thailand

The paddy field preparation for rice cultivation is one of the most significant operations contributing to high rice productivity. Recently, field preparation has been mechanized due to availability of power tillers and their matching implements (Ranjan and Pranv, 2021). Field preparation involves bund shaping and puddling at the onset of the paddy season. Bunds are shaped uniformly with a desired height and plastered with mud to reduce holes (Ranjan and Pranv, 2021). This helps reduce weeds, keeps the field ponded during the rainy season, and reduces seepage loss. Similarly, paddy fields are also found in dry regions, where adequate rainfall for rice growth is not expected. These are irrigated and require much water to maintain flooding. Evaporation of ponded water in these regions is high as are seepage losses compared with paddy fields in wet regions.

Conversely, the hydrological response in paddy fields largely depends on rainfall, irrigation management, and soil conditions (1.1). Farmers control water within paddy fields during rice cultivation (Kim et al., 2007). Additionally, rainwater can be stored in a paddy field as pond water or spill out from paddy levees. Therefore, paddy fields can buffer small to moderate levels of flooding depending on storage capacity. As paddy fields decrease with time, this rather complex effect on flood discharge results from changes in the water balance and associated water management of rice paddy fields (Kim et al., 2007). To evaluate the effect of paddy storage on stream discharge, it is crucial to understand and conceptualize the interaction of the paddy field with variations in rainfall and develop a paddy water balance model that integrates farm water management practices.

Paddy fields are also restricted by irrigation or drainage management of the canal. The planning and design of irrigation and drainage canals are essential for well-drained paddy fields, large-sized/small paddy fields, and rotational crop production. Delivery of irrigation water via a pipeline is expensive although it reduces maintenance costs and enhances stable water supplies in contrast to open channels, such as unlined or poorly constructed channels that lose water and deteriorate with time due to siltation and growth of weeds (Suozhu et al., 2020).

1.1.3 Components of Water Balance in Paddy Fields

Irrigation efficiency in flooded rice cultivation is paramount and relates to water requirements of paddy fields and crops as measures of water lost from the system (Huang et al., 2003). Water use efficiency is the ratio of dry crop biomass or grain yield produced to unit water transpired (used) by plants during cultivation (Hatfiled and Dold, 2019). Water balance in paddy fields comprises irrigation applications, rainfall, evaporation from ponded water or soil surfaces, transpiration, deep seepage losses, and percolation into the soil profile (Figure 1.1). The water balance of lowland rice fields has been widely evaluated (Nie et al., 2012; Tabbal et al., 2002). Similarly, the water balance of irrigation regimes influences the hydrologic relations of plant shoots which control crop root water uptake (Miyamoto et al., 2001; Parent et al., 2010). Previous research established that the hydraulic properties of roots of various crops have substantial co-regulation pathways that interact with root-soil systems (Miyamoto et al., 2001; Li et al., 2014; Matsuo et al., 2009). Therefore, drying and wetting conditions of AWD water regimes optimize their environment and soil-root hydraulic properties which determines the root profile distribution of rice in paddy soils. This has implications for yield due to the variable mechanical resistance of puddled and non-puddled soils (Kato and Okami, 2010).

A water balance helps to evaluate the efficiency of water usage in paddy fields and groundwater recharge (Chen et al., 2002):

$$\mathrm{I} + \mathrm{R} = \mathrm{E} + \mathrm{T} + \mathrm{S} + \mathrm{P} + \mathrm{D} + \Delta w \qquad (1.1)$$

where: I; the irrigation supply; R, rainfall; E, evaporation; T, transpiration; S, lateral seepage; P, percolation; D, surface drainage or runoff; and Δw is the change in ponded water depth or water storage in the soil profile; all in mm/day. However, the rate of water loss due to deep percolation is expressed using Darcy's formula:

$$\mathrm{v} = \mathrm{KI} \qquad (1.2)$$

where: v, velocity of percolation; K, coefficient of permeability and I, hydraulic gradient (Yukawa, 1992). The hydraulic gradient (I) is the change in hydraulic head per unit distance of travel in the soil layers.

$$I = \frac{H}{L} \tag{1.3}$$

Typically, L is constant for vertical flow and changes in H dominate the amount of percolation. Additionally, E is highest at early growth stages, when the leaf area index (LAI) is small, accounting for most evapotranspiration (ET) losses.

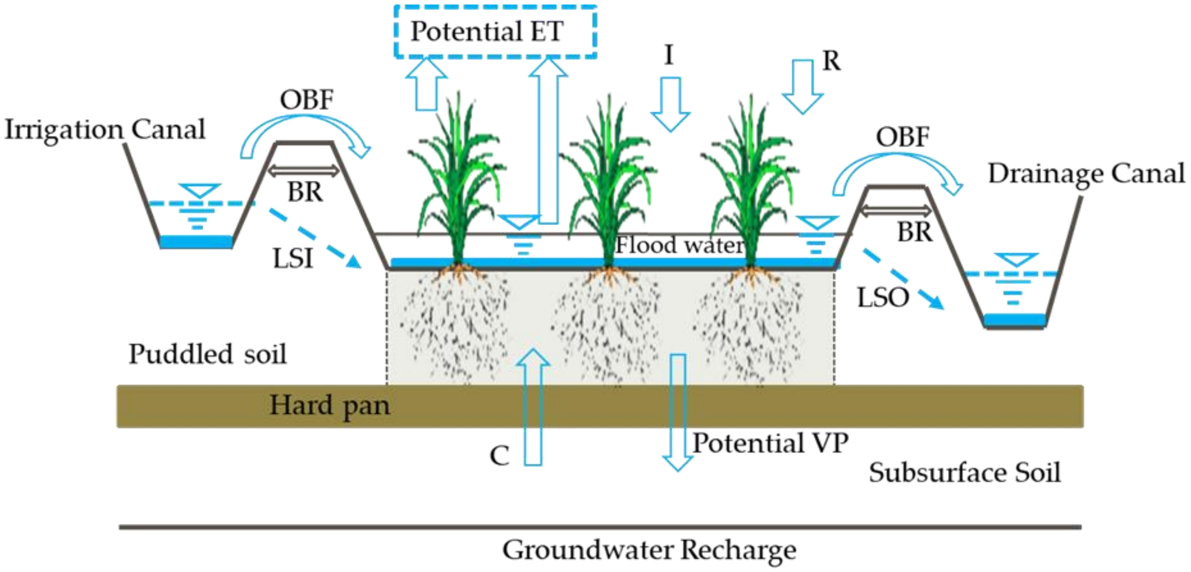


Figure 1. 1: Schematic Illustration of conceptual water balance in paddy fields

Where, C, capillary rise; Potential ET, evaporation, and transpiration; I, irrigation; OBF, over-bund flow; VP, vertical percolation; R, rainfall; LSI, Lateral seepage inflow from irrigation canal; LSO, Lateral seepage outflow to drainage canal.

1.2 Rice Paddy Water Requirements

Submerged paddy fields require much water due to percolation losses. Paddy water requirements vary widely due to soil properties and management, climate and season, rice variety, water management, and other practices (Table 1. 3). Sustainable water management is essential for crop survival, growth, and development and to produce economic benefits. Paddy crop water requirement is challenging; irrigation planning and design requirements for paddy fields must consider several paddy fields (units) with similar characteristics as a basic unit (Suozhu et al., 2020). Several unit blocks are integrated to form a beneficiary area. The minimum water requirement for the entire area can be estimated based on unit blocks or beneficiary areas – i.e., "regional irrigation requirement". Research indicates that the total water requirement of rice ranges from 750 to 2500 mm for an entire season; 150–200 mm for nursery preparation, 200–300 mm for field soaking and puddling of the main field, and 800–1200 mm applied in the main field from transplanting to harvest (Mote et al., 2022). The daily paddy-rice water consumption varies from 6 to 10 mm/day depending on agro-climatic conditions during crop cultivation (Mote et al., 2022). Irrigation planning and design decrease crop water requirements in paddy fields; the planned water requirement rate is at 10–20 mm/day, although actual water requirement rate may reach 20–30 mm/day (Mizutani, 1980; Fujii et al., 2009) due to the change from wet and semi-wet fields to dry fields. However, in most tropical regions the average evapotranspiration (ET) rate during the wet season is 4-5 mm/day, while in the dry season it is 8-10 mm/day. The total seasonal water requirement for rice fields (rainfall plus irrigation) is up to 2-3 times that for other cereals (Tuong et al., 2005). Therefore, it is crucial to maintain the recommended crop requirement depending on crop stage and other factors highlighted herein. Soil water deficit below saturation affects growth and yield due to reduced leaf surface area and photosynthetic rate via decreased stomatal conductance to CO_2 (gas) and photosynthetic metabolic potential (Lawlor and Tezara, 2009).

Field preparation activities for rice production include tilling, sowing, fertilizing, irrigating, harvesting, and post harvesting processes. Paddy rice production seasons vary amongst regions, with climate with some regions supporting more than one crop. For example, paddy cultivation in Japan has one production season. In central Japan, cultivation varies from April-May to August-October, while in southern Japan, the rice season is from April–May to August–September (Yoshino, 1993). In contrast, Bangladesh has three rice-growing stages: aus, aman, and boro. Aus is the pre-monsoon upland rice growing where rice is directly seeded/broadcasted in March-April and harvested in July-August. Aman season rice is either directly seeded or transplanted and relies on monsoon rains. Rice directly seeded in aman season has the same schedule as Aus, though the transplanting is done in July-August and harvested in November. Boro is dry season irrigated rice planted from December to early February and harvested between April and June (Shelley et al., 2016). Conversely, the suitable cropping calendar in East Africa countries such as Kenya, Uganda, and Tanzania is a combination of January-May and July-December, or February–June and August-January cultivations (Samejima et al., 2020). Mainly two rice varieties are cultivated in the world today: African rice (Oryza glaberrima Steud) and Asian rice (Oryza sativa L.). Additionally, Oryza sativa L. is furthermore divided into three groups: Indica, Japonica, and Javanica (Nayar, 2014).

Table 1. 3: Stage-wise water requirement for paddy rice. Source: www.agritech.tnau.ac.in

S/No	Stages of growth	Water requirement (mm)	Percentage of total water requirement (%)

1	Nursery	40	3.22
2	Main field preparation	200	16.12
3	Planting to panicle initiation	458	37.00
4	Panicle initiation to flowering	417	33.66
5	Flowering to maturity	125	10.00

1.2.1 Water Management in Rice Paddy Fields

Developing and promoting appropriate water management technologies to increase water efficiency in paddy fields without affecting yields is desirable and requires a holistic approach, including integrated crop, soil, and water management (Bouman et al., 2007). Water management in paddy fields starts from the design, distribution, application and use, and removal of excess water from fields with the intent to maximize crop production and improve water use efficiency and labour productivity (Odhiambo and Murty, 1996).

Water use and management techniques in irrigated paddy fields are practiced using the rice intensification system (SRI). Caution must be taken in promoting such techniques as "one-size-fits-all" solutions due to regional differences in paddy environments, and local and site-specific adaptations must be considered. SRI is believed to have originated in Madagascar and includes a suite of recommendations differing from conventional methods, including crop establishment-transplanting of single seedlings, transplanting in the square, irrigation management, weed control, and fertilizer application (Stoop et al., 2002). SRI techniques are based on close field observations of the biological characteristics of rice plants while manipulating the natural genetic potential (Berkhout et al., 2015). The promotion of SRI assumed that the system is appropriate and beneficial for poor and marginal farming communities because high yields can be realized without heavily investing in seeds and chemical fertilizers (Stoop et al., 2002; Uphov, 2002).

Many farmers have modified the original SRI to match their needs and paddy environments, although the impacts of water flow and hydraulic conductivity with SRI technologies have been less examined (Uphov et al., 2002). Rice production is strongly affected by water availability and yield increase is a function of increases in transpiration/water uptake and reduction in other water balance factors, i.e., evaporation, seepage, and percolation (Bwire et at., 2022b; Bouman, 2006). Water conservation and high crop water productivity can be realized through SRI practices since they include good agronomic practice that increases the harvest index resulting in more grains per unit water transpired by the crop (Bouman et al., 2007; Katambara et al., 2013).

Similarly, water-saving techniques are essential to help farmers cope with water scarcity due to climate change (Humphreys et al., 2005); these include: i) direct seeding; ii) saturated soil culture; and iii) Alternate Wetting and Drying practice (Katambara et al., 2013). Recently direct seeded rice has increased more in Asian countries where farmers seek higher productivity and profitability to offset rising costs and compensate for scarcity of farm labour (Balasubramanian and Hill, 2002). Direct seeding is a broadcast sowing/row seeding of dry rice seeds on dry (or moist) fields. While dry seeding contributes to more efficient water use, the Muda irrigation scheme in Malaysia (Cabangon et al., 2002) did not effectively reduce the total amount of water used or increase crop productivity. Classifications of directly seeded rice system are shown in Table 1. 4.

Table 1. 4: Classification of directly seeded systems.

Direct Seeding Systems	[1]Seed Condition	[2]Seedbed condition and environment	[2]Seeding pattern	[2]Where practiced
Direct-dry seeding	Dry	Dry soil, mostly aerobic	Broadcasting; drilling or sowing in rows	Mostly in rainfed areas and in irrigated areas with precise water control
Direct-wet seeding	Pre-germinated	Puddled soil, may be aerobic or anaerobic	Various	Mostly in irrigated areas with good drainage
Water seeding	Dry or pre-germinated	Standing water, mostly anaerobic	Broadcasting on standing water	In irrigated areas with good land levelling and in areas with red rice problem

Saturated soil culture (SSC) is a water management technique where the soil is usually kept near saturation by typically applying irrigation water at a depth of 1 cm daily after the disappearance of ponded water (Bouman et al., 2007). SSC reduces the hydraulic head of deeper ponded water and decreases seepage and percolation losses. Field experiments with SSC treatments show that water inputs decrease on average by 23% (range: 5–50%) compared to continuously flooded rice fields, with only a 6% (non-significant) reduction in yield (Bouman and Tuong, 2001).

1.2.2 AWD Practice in Rice Paddy Fields

In AWD, rice paddies are intermittently irrigated, except during the rooting, panicle formation, and flowering stages, reducing water use by 15-40% (Yamaguchi et al., 2016). Water application strategies in AWD practice are classified as: a) phreatic head-based or b) soil water potential (SWP) head-based criteria. The phreatic head-based criterion is conducted by measuring the water table or water level (WL) in an observation tube (well) installed 15-25 cm below the soil surface and irrigation is applied when water disappears in the tube (Fig. 3). The SWP is classified as: 1) safe AWD, when soil water potential (SWP) in the paddy-rice rhizosphere is allowed to drop below −20 kPa (SWP ≥ −20 kPa) or WL is allowed to drop ≤ 15 cm depth inside the water tube; 2) mild AWD, when SWP in the rhizosphere is permitted to drop to −45 kPa (SWP ≤ -20 kPa); and 3) severe AWD, when SWP in the rhizosphere is reaches -70 kPa (Shekar et al., 2019; Bouman et al., 2007).

1.2.3 AWD Recommendations

The most practical approach of AWD irrigation by farmers in the paddy field is using a field water tube ('observation pipe') (Yamaguchi et al., 2016). The perforated observation tube has holes (0.5 cm diameter) drilled at 2 cm apart throughout the buried length of the tube (Figure 1.2). Observation tubes are used to monitor water depth in the field using a graduated meter ruler. Diminished water depth is mostly due to evapotranspiration, deep percolation, and seepage losses (Mote at al., 2017). Usually, the tube is placed in a readily accessible location close to the bund (≤ 1 m away) for easy monitoring. The location should be representative of the average water depth in the field (i.e., it should not be in a high or low location) (IWMI, 2014). When the water level drops to about 15 cm below the soil surface, irrigation is applied to re-flood the field to a depth of about 5 cm. One week before flowering and during panicle formation period, the field is kept flooded, up to a depth of 5 cm of ponded water. After flowering, during grain filling and ripening, the water level is allowed to drop again to 15 cm below the soil surface before re-irrigation (Yamaguchi et al., 2016; IWMI, 2014). AWD can be introduced 1-2 weeks after transplanting or when crop height is about 10 cm, though when many weeds exist, AWD should be delayed for 2−3 weeks, to quell the weeds with ponded water (Lampayan et al., 2005). Fertilizer application, particularly nitrogen, is recommended on dry soil before irrigation, similar to traditional flooding (IWMI, 2014). Likewise, care should be taken during the installation and maintenance of the tube, including removing soil from inside the tube (siltation) and ensuring that the water level inside the tube during flooding is the same as outside the tube, if not the holes in the tube may be blocked with compacted soil and reinstallation is required (IWMI, 2014). Siltation is a problem due to clogging of perforations and has been reported to reduce the performance of AWD using observation water tubes (Mote et al., 2022). Relatively narrower water tubes are mostly affected by siltation. Paddy sediment and turbid water in catchments where rice is transplanted in puddled conditions may pass into water tubes, and after settling, siltation occurs (Latif, 2010). Huge siltation inside the large diameter (15 cm) observation tubes is rare. Similarly, soil siltation depth in AWD irrigation regimes was lower compared to continuous submergence (Mote et al., 2019). Notably paddy fields do not always require ponding and cultivation when such innovative technologies are applied, thus these need to be emphasized and promoted.

Generally, lowland rice-growing areas where soil can be drained in 5-day intervals are suitable for AWD though high rainfall may impede AWD. If rainfall exceeds water lost to evapotranspiration and seepage, the field will be unable to dry during the growing season. Farmers must avoid over-irrigation of fields and understand that water will be accessible once fields drain. AWD in rainfed rice is not recommended due to uncertain water availability when fields must be re-flooded (IWMI, 2014; Lampayan et al., 2005).

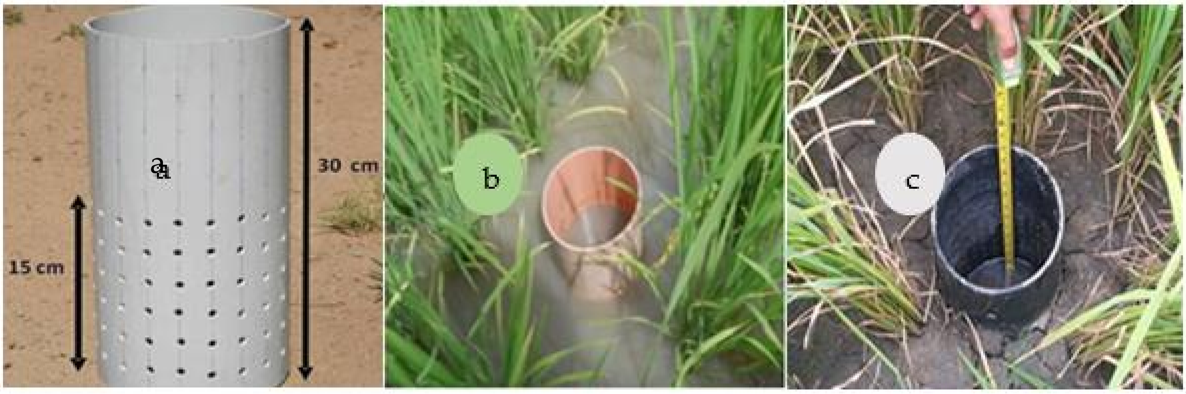


Figure 1. 2: Field application of AWD irrigation practice

Where a) field observations PVC water tube; b) flooding conditions, and c) water depth measurements using a meter ruler.

1.3 Literature Review: AWD Technology on Rice Paddy Cultivation

1.3.1 Crop Height, Yield, and Yield Components

Rice is sensitive to any water stress and unsaturated soil conditions (Bwire et al., 2022). Thus, it is not surprising that yield reduction may occur in AWD practice but may not be significant in some cases, if managed well. The degree of soil drying greatly affects yields (Carrijo et al., 2017). Any decrease in irrigation regimes tend to induce drought stress, contributing to a decline in net photosynthesis and reduced growth through the inhibition of cell elongation or cell division (Pascual and Wang, 2017). As noted, water application in paddy rice with AWD practice must be conducted once water drops to the threshold WL to avoid induced water stress. Research on water productivity and harvest indices for different safe

AWD water regimes, indicate that crop height after 40 days and growth after direct seeding was similar for both control (CF) and safe AWD regimes (when WL dropped to 5, 10 and 15 cm depth in observation tube) (Bwire et al., 2022).

Furthermore, if water declines to 15 cm in observation tubes, the soil is still near saturation and water is available for rice growth. Therefore, irrigation can be applied when the water level in the paddy rice field drops to 10–20 cm below the soil surface without significant yield reduction (Lampayan et al. 2009). The ponded water depth intermittently used in AWD regimes varies from 3 to 5 cm and WL will drop 5-10 cm in the observation tube by delaying irrigation from 2-8 days before re-irrigation (Bouman and Tuong, 2001). Such scenarios may vary depending on soil type, structure, and hydrological properties. However, yields in acidic soils with AWD practice were higher than in soils with a pH ≥ 7 (Carrijo et al., 2017). These differences can be due to the high percentage of exchangeable sodium (Na) which causes dispersion in alkaline soils (Abrol et al., 1985). This does not limit crop growth in flooded conditions, where rice has shallow roots, but it affects crop development with AWD practice since plant roots tend to grow deeper (Yang et al., 2004). Additionally, high levels of Na lead can be toxic to crops, which is not a problem under flooded conditions since Na leaches out of the root zone. Conversely, in AWD regimes with drier soils, higher Na concentrations can cause more uptake when the paddy rice variety is less tolerant to Na (Abrolet al., 1985). When AWD is practiced throughout the season, yield reductions were observed compared to when practiced in either the vegetative or reproductive stages (Carrijo et al., 2017).

Not all the rice crop tillers develop to mature tillers; some become dormant when young and die later depending on environmental and nutritional conditions (Horie et al., 2005), thus affecting final yield. The rate of the crop recovery due to reapplication of water depends on soil conditions, such as soil water, pre-drought intensity, and duration of soil drying (Xu et al., 2010). In contrast, short-duration soil drying does not affect crop growth, rice tillering, and general yields (Bwire et al., 2022).

1.3.2 Water Use Efficiency and Productivity

Several studies on AWD practice have shown increased water productivity where water inputs are reduced. Various field experiments comparing AWD to continuous flooding have been conducted in Asia, including China (Cabangon et al. 2004; Yao et al. 2012), India (Mahajan et al. 2012) and The Philippines (Cabangon et al. 2011), all confirming the high water-saving potential of AWD.

AWD irrigation reduces water use on average by 26% compared to C.F., although severe AWD practice reduces water by 33% with corresponding yield reductions (Carrijo et al., 2017). With increasing global water scarcity and dwindling water resources, AWD irrigation can benefit sustainable water use. However, comparing the cost of water and rice, higher water productivity does not necessarily mean that AWD practice is more economical for farmers. Research on the economic viability of different AWD treatments shows the lowest profit in the treatment with highest water productivity, therefore factors other than water productivity must be considered (Nalley et al., 2015). Nevertheless, AWD technology significantly reduces irrigation frequency compared to typical rice paddy practices, lowering irrigation water consumption by 25%, as well as fuel used for water pumping by 30 liters per hectare (Siopongco et al., 2013).

1.3.3 Paddy Soil Hydrological Properties with AWD Practice

Paddy soils generally have high clay content, water-holding capacity, and nutrients (Hamoud et al., 2018). Paddy soils typically consist of at least 35% clay; thus, they are clay-textured, according to USDA (1999). The formation of cracks in heavy clay soils affects agricultural water and crop production, a characteristic feature of paddy soils with AWD. practice (Haque et al., 2021). Alternatively, swelling and shrinkage in paddy soils are driven by decreased soil moisture and clay content that differ spatially (Hamoud et al., 2018; Dinka and Lascano, 2012). Periodic wetting and drying patterns in paddy soils during AWD practice is another factor that promotes swelling, shrinkage, and creation of cracks in the soil surface due to discharge of water from the clay microstructures, thus the soil matrix shrinks (Bottinelli et al., 2016; Haque et al., 2021). These cracks are less conspicuous with continuous flooding (Sander and Gerke, 2007; Yoshida and Adachi, 2004). Hydrological properties of paddy soils are significantly changed by cracks. Wide and deep cracks, transfer more water quickly from the soil surface to subsurface soil layers (Tan et al., 2013). The amount and extent of cracks occurrence controls the preferential routing of water losses via percolation and seepage (Stewart et al., 2015). Therefore, cracks significantly affect the amount of water that needs to be applied.

Cracks create preferential flow pathways, facilitating water infiltration (Liu et al., 2003) and increase the risk of groundwater pollution via fertilizer, pesticide, and herbicide percolation (Jarvis, 2007). These pathways allow water to bypass the soil matrix (Hardie et al., 2011). Evidence from field research indicates that 70–85% of water flux may be attributed to preferential flow. This creates challenges for predicting water and solute movement in field conditions (Sidle et al., 1977; Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988). Cracks formed during soil drying increase hydraulic conductivity; during wetting, crack closure reduces the infiltration rate (Liu et al., 2003). Little is understood about changes in the hydraulic properties during drying and wetting within the paddy rhizosphere with AWD practices in general and safe AWD practices at each crop growth stage remain elusive.

1.3.4 Redox Potential and AWD Practice

Although water savings are achieved with AWD practice, savings can be improved by modifying the rooting behavior of rice cultivars (Price et al., 2013). AWD has potential to alter macro and micronutrient availability and uptake. Aerobic growth favors enhanced selenium accumulation in rice (Li et al., 2010), while decreasing arsenic uptake (Xu et al., 2008; Norton et al., 2012). Arsenic accumulation increases in anaerobic soils because inorganic arsenic is present as arsenite (as opposed to arsenate in aerobic soils), the former which is more readily taken up by plant roots (Brammer and Ravenscroft, 2009).

The AWD regime affects soil redox potential since metals in pore water and the readily exchangeable solid phase pool vary significantly. Research on these trends at relevant temporal and spatial scales is limited (Adam et al., 2013). Soil redox potential (Eh) influences net NH_4+ (de) fixation, which refers to both fixation and de-fixation of NH_4 in paddy soils through nitrogen (N) fertilizer application. All structural Fe_3^+ in phyllosilicates is biogenically reduced with a consequent increase in the negative charge of clay minerals, which creates strong action between NH_4 cations and clay minerals at low Eh (Pentrakova et al., 2013; Schneiders and Scherer, 1998). The effect of Eh on NH_4+ (de) fixation is also indirect through its control on the occurrence of external N transformation processes, including mineralization and (de) nitrification, that could affect the exchangeable NH_4+ concentrations and dynamic balance with fixed NH_4 (Cucu et al., 2014).

Table 1. 5: Summary of impacts of AWD irrigation practice; yields, water saving and water productivity.

S/N	Component	Details	Authors
1	Wp, WUE, Water Saving	Higher Wp (1.74 g L^{-1}) in AWD compared to CF (1.23 g L^{-1})	Chapagain and Yamaji, 2010
		WUE (85.55 (kg ha^{-1} cm) in AWD with quite a large water saving (15 cm) compared to continuous submergence	Rahman and Sheikh, 2014
		Water saving of 15–20% with AWD without a significant impact on yield	Cabangon et al., 2004
		A 26.34% reduction in water use and only a 6.40% reduction in grain yield compared to the CF	Bwire et al., 2022
		Water application once in 7 days consumed the lowest amount of water (80.30 cm) and saved 41% water	Ganesh, 2000
		Water savings in AWD by 40–70%, 20–50% and 50% compared to CF	Zhao et al., 2010

2	Yield components	AWD irrigation regimes consumed water to the 50.9–82.1% of CF (1390 mm), with water saving (13.8–36.4%) and water productivity (1.148 to 1.266 kg m^{-3})	Mote et al., 2017
		AWD improves WUE and yields with 5, 7 and 10 days of irrigation interval	Yang and Zhang, 2010; Latif, 2010
		Average grain yield of 5.8–7.4 t ha^{-1} with AWD irrigation methods and 7.5–7.6 t ha^{-1} with continuous submergence	Mote et al. 2016
		Soil drying period of 8 days gave the highest yield (7.13 t ha^{-1}) compared to CF (4.87 t ha^{-1}) in Kenya	Omwenga et al., 2014
		Highest grain yield (5.9—6.2 t ha^{-1}) with irrigation schedule when water table dropped to 15 cm below ground level in Bangladesh	Paul et al., 2013
		Water application intervals of 5 and 8 days with CF produced statically the same grain yield. (7342, 7079 and 7159 kg ha^{-1}, respectively)	Ashouri, 2014
		Grain yield was higher in saturated condition (7.6 t ha^{-1}) compared to CF (7.1 t ha^{-1}) in Malaysia	Sariam and Anua, 2010
		Application of Safe AWD levels did not result in loss of rice yield	Buresh, 2010
		Increases rice yield by 10% with AWD	Yang et al., 2009

Where: Wp-Water productivity; WUE-Water use efficiency; Continuous flooding method

1.3.5 GHG Reduction and Soil Carbon Dynamics with AWD Practice

Recently, increased human activities have influenced global climate where water and greenhouse gas emissions are two key factors affecting climate (Siopongco et al., 2013). Besides, AWD technology has been proven as a GHG mitigation measure, particularly reducing CH_4 emissions up to 50%. CH_4 is produced anaerobically by methanogenic bacteria that thrive well in paddy rice fields (Figure 2.3). Hence, traditional flooding in paddy rice catchments is the largest source of methane emissions, the second largest anthropogenic source after ruminant livestock (Siopongco et al., 2013). Previous studies have indicated that AWD technology can reduce methane production up to 60% (Uprety et al., 2012).

In contrast, AWD influences the production of nitrous oxide (N_2O), another potent GHG gas. The N_2O has a global warming potential (GWP) of 298, implying that it is 298 times more effective in trapping heat in the Earth's atmosphere than CO_2, while CH_4 has a GWP of 25 (IPCC, 2011). N_2O emissions tend to increase due to increased nitrification and denitrification activities, when the soil conditions constantly change between anaerobic and aerobic conditions, and related changes in soil redox potential. However, data on N_2O emissions under different water management regimes are scarce (Siopongco et al., 2013).

Additionally, the campaign and polices for expansion of rice production to meet future demands need to match appropriate water conservation and management approaches. Understanding the carbon cycle in rice cropping is critical to interpreting the potential for more climate-friendly grain production (Runkle et al., 2018). Soil organic matter is crucial for both plant and CH_4 productivity and quantifying the carbon balance helps constrain estimates of change in organic matter.

The sustainability of rice yields depends on soil fertility, which is related to soil organic carbon (SOC) (Lal 2005). While few studies have addressed the effects of water-saving irrigation management strategies such as AWD on the soil C balance, much attention has been placed on reduction of consumptive water use without affecting yields. The loss of SOC due to changes in water management contributes to yield reductions (Grace et al 2003). Therefore, quantifying SOC losses is important to predict the impacts of water saving irrigation on yield and yield growth, as well as GHG emissions and global warming potential (Livsey et al., 2019). Likewise, a comprehensive accounting is needed to place GHG reduction and carbon dynamics in a broader context thus balancing reduction in CH_4 emissions with increase in CO_2 production (Runkle et al., 2018).

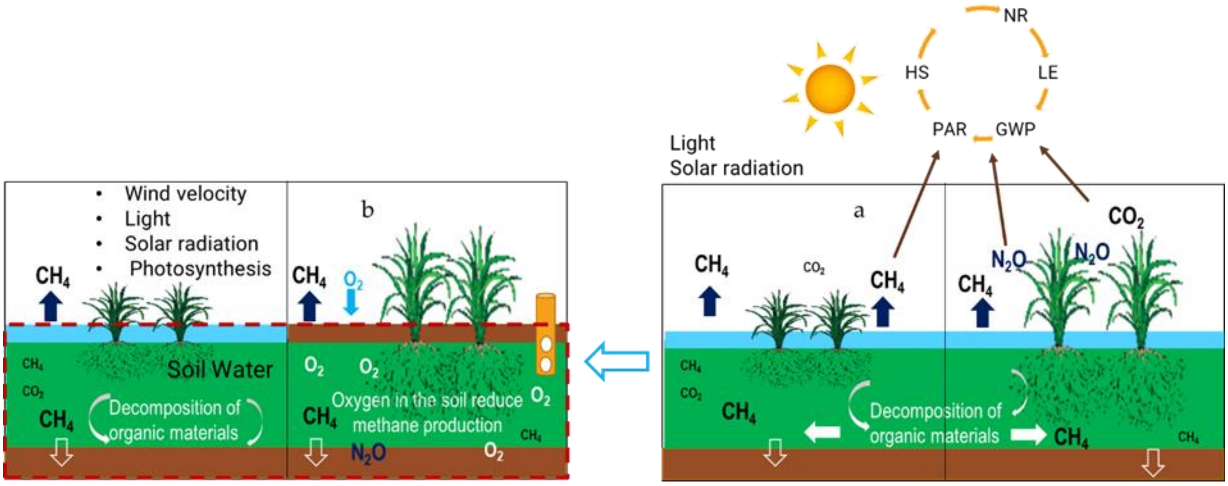


Figure 1. 3: Illustration of greenhouse gas interactions in paddy field and AWD practice.

Where a) Anaerobic respiration in absence of oxygen under traditional flooding conditions (CF), and b) Aerobic respiration in presence of oxygen due to soil drying conditions under AWD Irrigation. GWP is global warming potential; PAR is photosynthetically active radiation; HS is sensitive heat; NR is net radiation; LE is latent heat.

1.4 Research Goal, Questions and Objectives

The overall goal of this research was to investigate the Alternate Wetting and Drying (AWD) Irrigation practice under different water regimes: continuous flooding (CF) and AWD water regimes, for agricultural water management in paddy fields. The application of AWD practice, developed by IRRI (IWMI, 2014) is based on triggering criteria for irrigation: phreatic head or matric potential head; the phreatic head, requires a perforated pipe (observation well) is installed at 15-25 cm water table below the soil surface and irrigation is applied when the water level (WL) in the tube disappears.

Similarly, the matric potential head-based criterion involves applying water when the matric potential (WSP) in the rootzone reaches between -20 kPa to -70 kPa measured by the tensiometers (Shashank et al., 2019). The duo leaves unresolved uncertainties including mismatch in application comparing WL and SWP influenced by the soil type, changes in soil hydraulic conductivity due to soil drying and wetting patterns, rice cultivator, growth stage and climatic changes. These causes variation in non-flooded days, cracks formation and changes in hydrologic characteristics of paddy soils, leaving some three major rising questions to be answered in this study including:

i. Why AWD technology is less practiced in Sub-Saharan region and East Africa in particular.
ii. Can AWD irrigation practice be applicable throughout the paddy rice cultivation season. IRRI recommends keeping paddy fields flooded from booting to flowering stage thus for 4 weeks, due to fear of decline in yield (IWMI, 2014).
iii. What is the influence of AWD soil wetting and drying regimes on the hydrological processes and irrigation water use in paddy fields?

Therefore, the objectives below were key to answering the highlighted questions above.

i. To assess the potential of AWD irrigation practice in Sub-Saharan Africa, East Africa
ii. To assess the effect of AWD water regimes on agronomic performance and soil hydrological conditions of paddy rice throughout the cultivation period. Determining the critical weather parameters that influence evapotranspiration and soil water balance of paddy rice is vital.
iii. To quantitively evaluate and understand the effects of AWD water regimes on water flow and soil water balance components in directly seeded paddy rice at pot scale using HYDRUS-1D Model simulations.
iv. To explore the influence of deficit irrigation scenarios on root water uptake for paddy rice cultivation, using HYDRUS-1D Model. This is important for irrigation planning. Further, develop a smart water management system based on Internet of Things (IoT) for agricultural field monitoring and application of irrigation scenarios in Uganda and Africa.

1.5 Research Purpose

Climate change is threatening the water cycle, in addition to CF mostly practiced in in East African (EA) region, contributing to water wastage, droughts and calling for adoption and promotion of water management in paddy fields. The purpose of this research was to develop detail understanding and gain knowledge on the Alternate Wetting and Drying (AWD) irrigation for improving water management in paddy rice fields in Uganda and EA region. This came at a right time when the Ugandan government is emphasizing and working on the rehabilitation and expansion programs of paddy irrigation schemes in the country to improve food security (Bwire et al., 2022a). Likewise, the need to pilot paddy water management programs and support the smallholder farmers in the region through knowledge transfer and integration of AWD in their farming approaches to improve water use, management, and rice grain yields.

1.6 The Research Scope and Structure of PhD Dissertation

The research focused on investigating the AWD practice for developing agricultural water management in paddy fields. The study dissertation entails six chapters that make the research objectives (Figure 1.4). Chapter one, introduction presents the detailed background: global water issues and rice production; climate, highlighting the goal, and objectives of the research. Previous studies have been cited to explain the gaps, and purpose of the research in achieving the study objectives.

Chapter 2 focuses on literature synthesis to understand the potential of AWD irrigation in East Africa. The synthesis approach encapsulated the brainstorming and formulation of research questions and defined critical areas: paddy rice cultivation systems, irrigation systems, climate change and food insecurity, government policies. The chapter summarizes the findings information and provides future direction for piloting AWD and water management for increase rice productivity in East Africa. The chapter explored some of the current water management and soil water conservation practices including system of rice intensification (SRI) and AWD irrigation practice in detail—applications and recommendations, the gaps and the skepticism for the adoption of the AWD technique by farmers in East Africa.

Chapter 3 describes AWD regimes and paddy rice cultivation experiments carried out for three seasons from February 2021 to March 2022 in glass greenhouse (phytotron), Tokyo University of Agriculture and Technology, Japan. AWD regimes were defined—AWD5, AWD10 and AWD15, when water level in observation tubes dropped to -5, -10 and -15 cm below soil surface compared with continuous flooding (CF) s control, when ponded water dropped to the ground surface. The measurements of crop agronomic performance of paddy rice and soil hydrological conditions including crop growth, tiller, yield components, water level and soil water pressured heads are described. The observation and findings from this chapter gave way for chapter 4 on quantitative evaluation and understanding of the water flow in paddy soils under AWD regimes.

Numerical evaluation of soil water flow and water balance components at pot scale using HYDRUS-1D is described in Chapter 4. This chapter also highlights the characteristics of the experimental pot rice cultivation system. Evapotranspiration (ET) is one important input parameter required for HYDRUS simulations. This was estimated using the standard Penman-Monteith FAO (PM-FAO) method. Similarly modification of crop evapotranspiration (ETc) in HYDRUS-1D simulations was performed since PM-FAO method was inadequate to estimate ET in the closed system–phytotron with pot paddy rice cultivation conditions.

Further understanding of soil water balance and root water uptake in paddy condition at pot scale was simulated with deficit irrigation scenarios in HYDRU-1D, important for irrigation planning. However the development of IoT smart agricultural water management system for application of deficit scenarios is highlighted in this chapter, for future field implementation of irrigation scenarios and AWD in East Africa. Finally chapter 6 provides the general conclusion of the dissertation, summarizing the key research findings, contributions of the study and recommendations for future research. All this is summed up in the schematic illustration below (Figure 1.4).

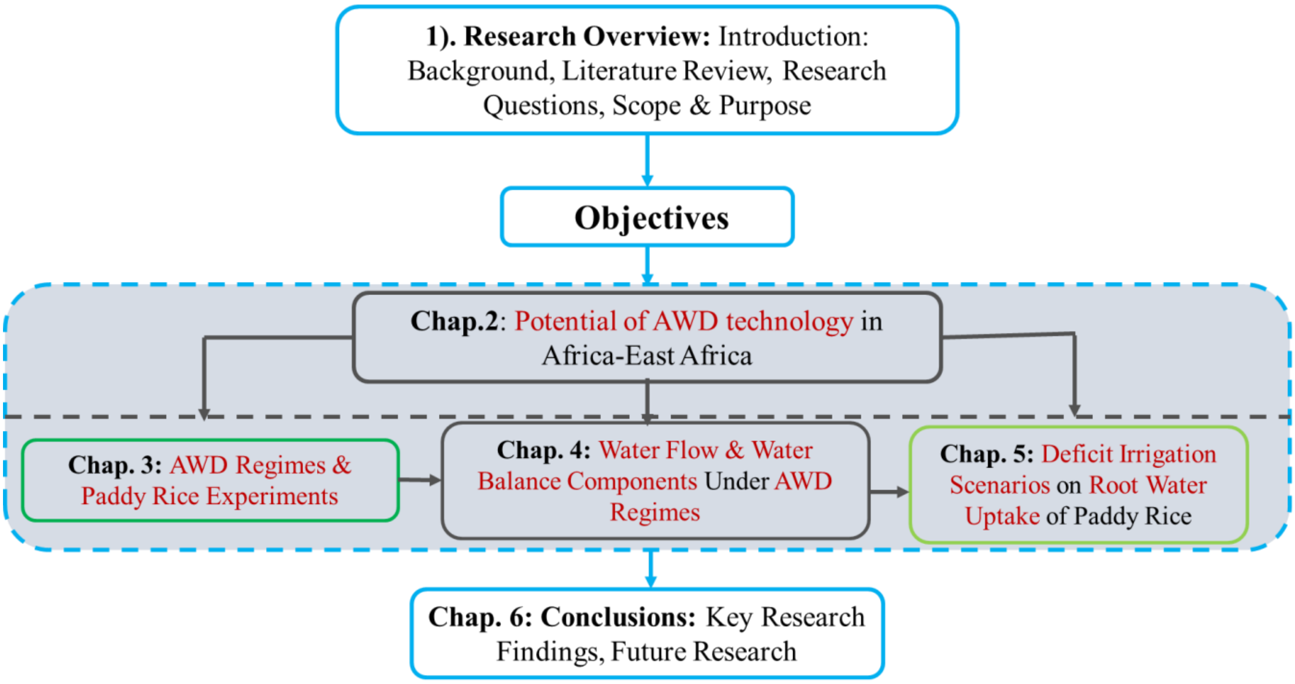


Figure 1. 4: The schematic structure of PhD study dissertation

2 Chap. 2: The Potential of AWD Technology in East Africa

In this chapter, literature synthesis was conducted to assess the potential of AWD technology in East Africa. Several research questions, including why AWD is less practiced in the region were formulated, current governments supporting policies and water management practices to (i) unveil critical gaps and core issues on paddy rice production systems, water management and food security in four EA countries (Uganda, Kenya, Tanzania, and Ethiopia) and (ii) examine future trajectories to improve paddy rice production in the region for building stable food security under threats of climate change.

2.1 Review Flow Approach

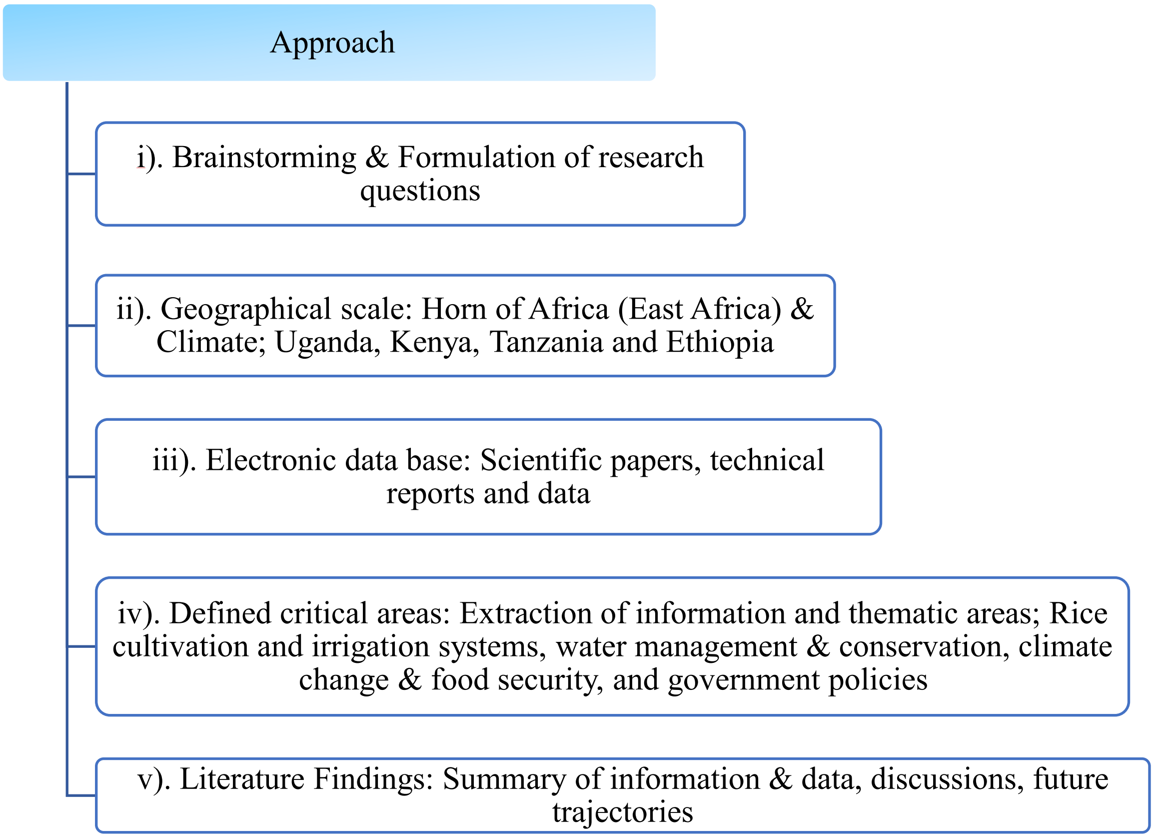


Figure 2. 1: Illustration flow of the literature synthesis. Adapted from Khan et al., 2003; Akoko et al., 2021.

2.1.1 Background and Climate of East Africa

For a long time, Uganda, Tanzania, and Kenya were referred to as EA, including recent reference to these nations based on climate (Nicholson, 2017). Similarly, other authors have used the terminology "Greater Horn of Africa" (GHA) in a broader analysis of other sectors (Schreck and Semazzi, 2004). Currently, EA primarily comprises the following countries:

Kenya, Uganda, Tanzania, Ethiopia, Eritrea, Djibouti, Somalia, South Sudan, Rwanda, and Burundi. However literature synthesis for this chapter considered four EA nations – Uganda, Kenya, Tanzania, and Ethiopia – as the major rice producers in the region (Figure 2.2). These four countries occupy a total area of 2.88 million ha with 0.241, 0.583, 0.945, and 1.112 million ha, respectively, in rice production.

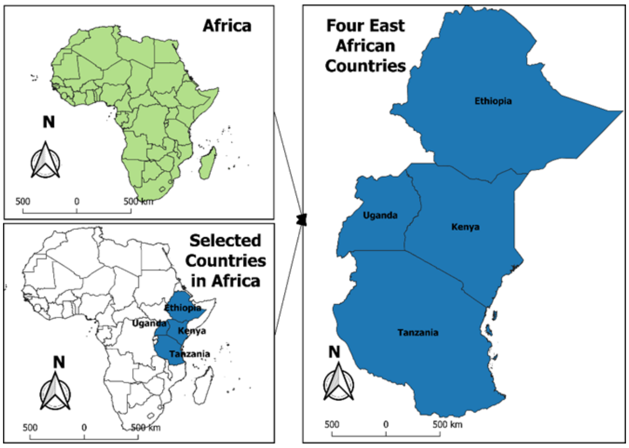
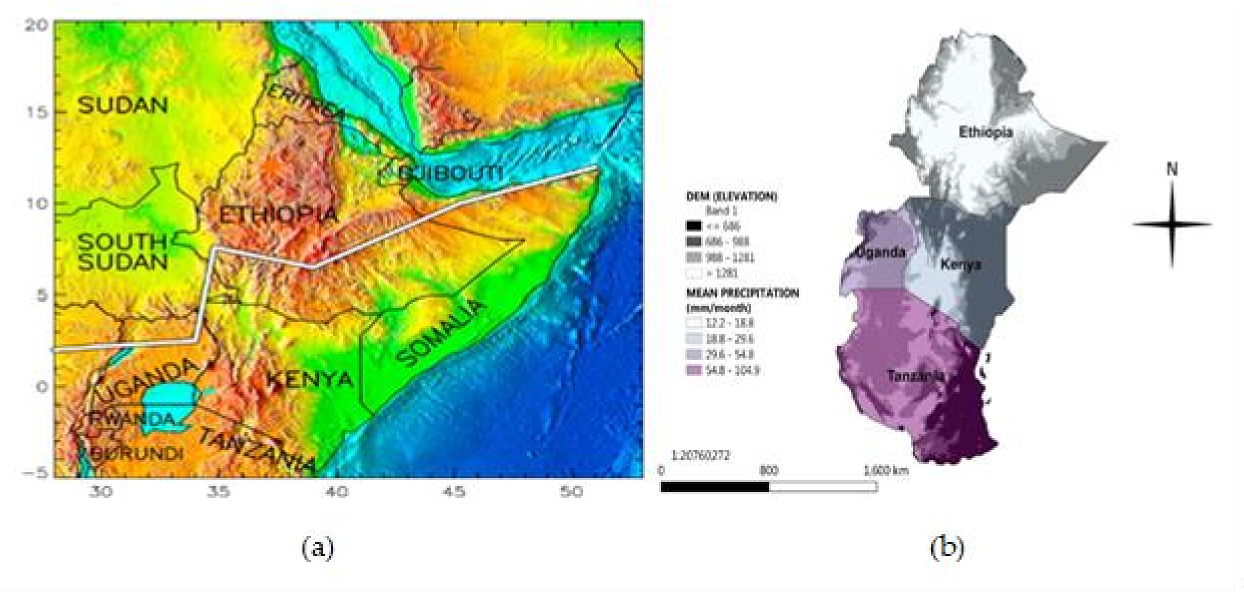


Figure 2. 2: Map of four East Africa countries: Uganda, Kenya, Tanzania, and Ethiopia

The region lies within the tropical latitudes and the climate varies from arid conditions in the east to more humid conditions in the west. The distinction of climatic types is essential because most EA countries experience a bimodal rainfall regime and receive high rainfall, with peaks in both the boreal spring and autumn (Haile et al., 2019). Several factors influence rainfall and climate, including altitude, proximity to the warm Indian Ocean, Inter-Tropical Convergence Zone (ITCZ) migration, and location of dominant atmospheric high- and low-pressure systems (Daron, 2014). Climate types are described as: 1) equatorial climate, which lies 5°N and 5°S of the equator; 2) moist tropical climate/modified equatorial climate in central and western Uganda and parts of northern Uganda (Figure 2.3a; Bwire et al., 2017); 3) dry tropical climate in several parts of EA, e.g., semiarid regions in west Karamoja, southern Nyika plateau, and parts of western Tanzania; 4) semiarid and arid climate in northern Kenya, e.g. the Chalbi desert, northeastern Uganda, 5) montane climate/alpine climate proximate to mountain peaks of EA; and 6) tropical monsoon climate in coastal regions of EA. Additionally, the equator passes through Uganda and Kenya. Regions closer to the equator typically have two rainy seasons with rainfall peaks around April and October, particularly punctuated in the most arid areas (Daron, 2014).



(a) (b)

Figure 2. 3: Map of Location a) equatorial (southern sector) and summer rainfall (northern sector) regions superimposed upon schematic map of East Africa topography.

Source: Nicholson, 2017, b) precipitation distribution and variability (developed in QGis 3.28.1) in EA: Uganda, Kenya, Tanzania, and Ethiopia. High resolution gridded precipitation data sets, 1900-2021 (Harris et al., 2020, https://crudata.uea.ac.uk/cru/data/hrg/)

2.1.2 Agricultural Development in East Africa

Agriculture in EA is mainly practiced by smallholder farmers. The traditional smallholder agriculture in EA is rainfall dependent, with low yields and susceptible to climate change. This has affected small-scale farmers, who contribute to up to 90% of agricultural production (Salami et al. 2010; Wiggins and Keats, 2013), rendering them vulnerable to a vicious cycle of poverty and food insecurity (Pablo and Gillerrock, 2013). Nevertheless, agriculture remains the main contributor to employment and accounts for 23.6 -35.6% of GDP among the four EA countries (Table 1). However, the agriculture share of EA's GDP has declined drastically since 1980 (Fratkin, 2001) from 47.2% to nearly 25% in 2001, though currently fluctuating in the region depending on the country (Table 2.1). But agriculture still accounts for about 75% of the labour force in all the countries, underscoring the importance of the sector in job creation and poverty reduction (Salami et al., 2010). Given these statistics, the obvious question is, why does the region remain in this state?

To describe the smallholder agriculture sector, one needs to understand who the smallholder farmer is. Smallholder agriculture generally refers to rural producers, mostly in developing countries, who use mainly family labour within the farm as the primary source of income (Nakawuka et al., 2017). However, the definitions to scale are relative to regional and national contexts, and "smallholders" in developed countries may have farms (and incomes) many times larger than those in developing countries (Morton, 2007).

One of the challenges of smallholder farmers is low productivity emerging from limited knowledge, access to markets, credit, and technology (Salami et al., 2010). Recently, this has been impacted by volatile food and energy prices and the global financial crisis. In addition, rain-fed agricultural systems remain increasingly vulnerable to climate change disruptions, especially in sub-Saharan and EA regions, where only 6% of agricultural land is irrigated (Palay, 2021). The major crops include cereals and grains (e.g., rice, maize, sorghum, finger millet), root crops, banana tea, pyrethrum, sisal, cut flowers, coffee, cotton, and tobacco. Coffee, cotton, horticulture produce, and tea are the main export crops. Despite the significant potential to enhance agricultural production, the role of smallholder agriculture in food security and support of smallholder farmers to increase crop productivity amidst climate change remain major obstacles. These require knowledge and technology transfer, training, and access to agricultural inputs, but also strengthening the policies that enhance access to both input and output markets (Salami et al., 2010).

Table 2. 1:Sector contribution of GDP of East African countries for the period of five years; 2016-2020.

Country	Key Sectors	2016	2017	2018	2019	2020
		Percentage (%) of each sector				
Ethiopia	Agriculture	34.699	33.779	31.219	33.633	35.558
	Industry	21.933	23.582	27.306	24.822	23.102
	Exports	7.812	7.629	8.373	7.940	7.127
	Imports	27.087	23.474	22.827	20.875	16.879
	Revenue	9.358	9.445	8.973	7.788	7.105
	Military	0.695	0.666	0.639	0.588	0.481
Kenya	Agriculture	20.035	20.894	20.315	20.861	22.621
	Industry	18.162	17.504	17.313	16.931	17.404
	Exports	13.250	12.737	12.542	11.428	9.640
	Imports	21.615	23.258	21.873	20.331	17.594
	Revenue	19.066	21.146	18.679	19.098	16.764
	Military	1.349	1.289	1.266	1.168	1.105
Tanzania	Agriculture	27.444	28.742	27.869	26.546	26.737
	Industry	24.858	25.100	27.008	28.620	28.675
	Exports	16.350	15.140	14.739	16.008	14.295
	Imports	19.070	17.099	17.903	16.951	15.309
	Revenue	12.403	13.571	13.906	0.000	0.000
	Military	1.094	1.056	1.055	1.018	1.026
Uganda	Agriculture	22.660	23.459	23.250	22.946	23.929
	Industry	26.166	26.031	26.236	26.620	26.491
	Exports	12.427	16.661	15.087	17.109	15.415

Imports	18.782	20.176	21.551	22.252	21.586
Revenue	11.962	12.366	12.477	13.096	12.854
Military	1.046	1.096	1.226	1.770	2.597

2.1.3 History of Irrigation and Rice Production in East Africa

Supplemental irrigation during dry periods for crop production has been used in EA. For example, spate irrigation in Kenya has been practiced for more than 500 years along River Tana and in Marakwet, Keiyo, West Pokot, and Baringo districts (Ngigi, 2002; Oduori and Njeru, 2016). Rice was irrigated along river valleys around Kipini, Malindi, Shimoni and Vanga in the early 19th century. During the construction of the Kenya-Uganda railway, some irrigation activities were undertaken by Asian rail workers between 1901 and 1905 around Kibwezi and Makindu (Ngigi, 2002; Oduori and Njeru, 2016). In the 1930s, crop production commenced in some swampy areas in central Kenya and cash crops such as coffee, pineapple, sisal, and lucerne were introduced. This foresaw the development of public irrigation schemes under government control, including in Mwea, Hola, Perkerra, Yatta and Ishiara in Kenya (Ngigi, 2002).

Similarly, smallholder irrigation in Uganda is believed to have started in the early 1900s from Acholi, northern Uganda, where water divisions from rivers and streams were stored in trenches and applied to crops when needed (Watson, 1952). Rice planting in swampy areas started in eastern Uganda before World War II, while swamp reclamation commenced in 1943 in Kigezi, southwestern Uganda (Carruthers, 1970). The establishment of public irrigation schemes began in 1948 when diversion structures and bunds for spate irrigation, river diversions, small dams, tanks, and windmills were constructed in northeast Uganda (Nakawuka *et al*. 2017). Additionally, the development of larger government irrigation schemes, such as the Odina, Kiige, Labori, Ongom and Atera schemes, started in the 1960s. Furthermore, several public and private smallholder schemes, such as Kakira sugar estate, Olweny, Kibimba, Doho, and Agoro, were established. Recently, the Ugandan government has embarked on rehabilitation of irrigation schemes (e.g., Agoro and Olweny) to increase rice production and support the growing population (Bwire *et al.,* 2022b). Various crops are grown in these schemes using border, furrow, or sprinkler irrigation systems. Rehabilitation works were completed in 2013 in Mobuku, Doho, and Agoro public schemes (FAO, 2015b).

Traditional irrigation systems are said to have been practiced in Tanzania hundreds of years ago characterized by temporary diversion weirs and natural canals to control water flow. The weirs washed away during heavy rains and were reconstructed after each rainy season. Therefore, extensive water losses occurred in these canals (Matlock, 2008). Traditional irrigation practices were mainly furrow and flood irrigation in semiarid parts of Tanzania in the 1920s (Tagseth, 2008). However, in 1948, the Kilangali rice irrigation scheme of 1000 ha was established by the government in Morogoro Region, and more farmer-managed traditional smallholder schemes were established in the 1950s. Most irrigated areas and schemes in Tanzania use surface water; only 0.2% of irrigated areas use groundwater (Ministry of Water and Irrigation, 2009).

Evidence of past irrigation practices in Ethiopia is scarce. Formal irrigation on private farms using river diversions or motorized pumps in the Upper Awash valley is believed to have commenced in the 1950s to produce vegetables, horticultural crops, cotton, and sugarcane. This expanded to other parts of the Rift Valley region in the 1960s (Girma Awulachew, 2007). In the 1970s the Ethiopian government embarked on developing modern communal schemes using the diversion of streams and rivers, with some employing micro-dams for water storage. Most irrigation in Ethiopia occurs in the Rift Valley, specifically the Awash basin; by 2001, 62% of Ethiopia's irrigated area was in the Rift Valley region, with 39% in the Awash basin (Frenken, 2005). Most of the irrigation in Ethiopia uses surface water with water transported to fields mainly by gravity for application via furrow irrigation as the dominant method, similar to other countries of EA.

As a vital and increasingly popular crop in EA, rice is primarily grown by smallholder farmers using simple technologies on small landholdings (average of 2 ha). Three rice ecosystem production schemes exist: (i) rain-fed lowland; (ii) irrigated low-land/paddy; and (iii) upland production systems (Akongo et al., 2017). Additionally, the region has significantly increased the area in rice production and productivity during the past 20 years (Figure 2.4a), with most of the production from paddies. EA has huge potential for expansion of rice production with Tanzania the leader of rice area and production with > 1.5 million ha of land and 4.5 million tons of rice yield in 2020, > 85% of the total area and yields from the other three EA countries combined. The high production and development of the rice sub-sector in Tanzania is attributed to numerous factors including the availability of land suitable for rice cultivation (21 million hectares, half of all arable land); sufficient freshwater resources to support irrigation development; and the increasing population and urbanization increasing food demand at local and regional levels (Mkonda and He, 2017). Furthermore, EA has contributed > 10% of Africa's total rice production in the last five years (Figure 2.4c). The introduction and expansion of rice production in suitable areas may be an option to achieve food security and self-sufficiency within the region.

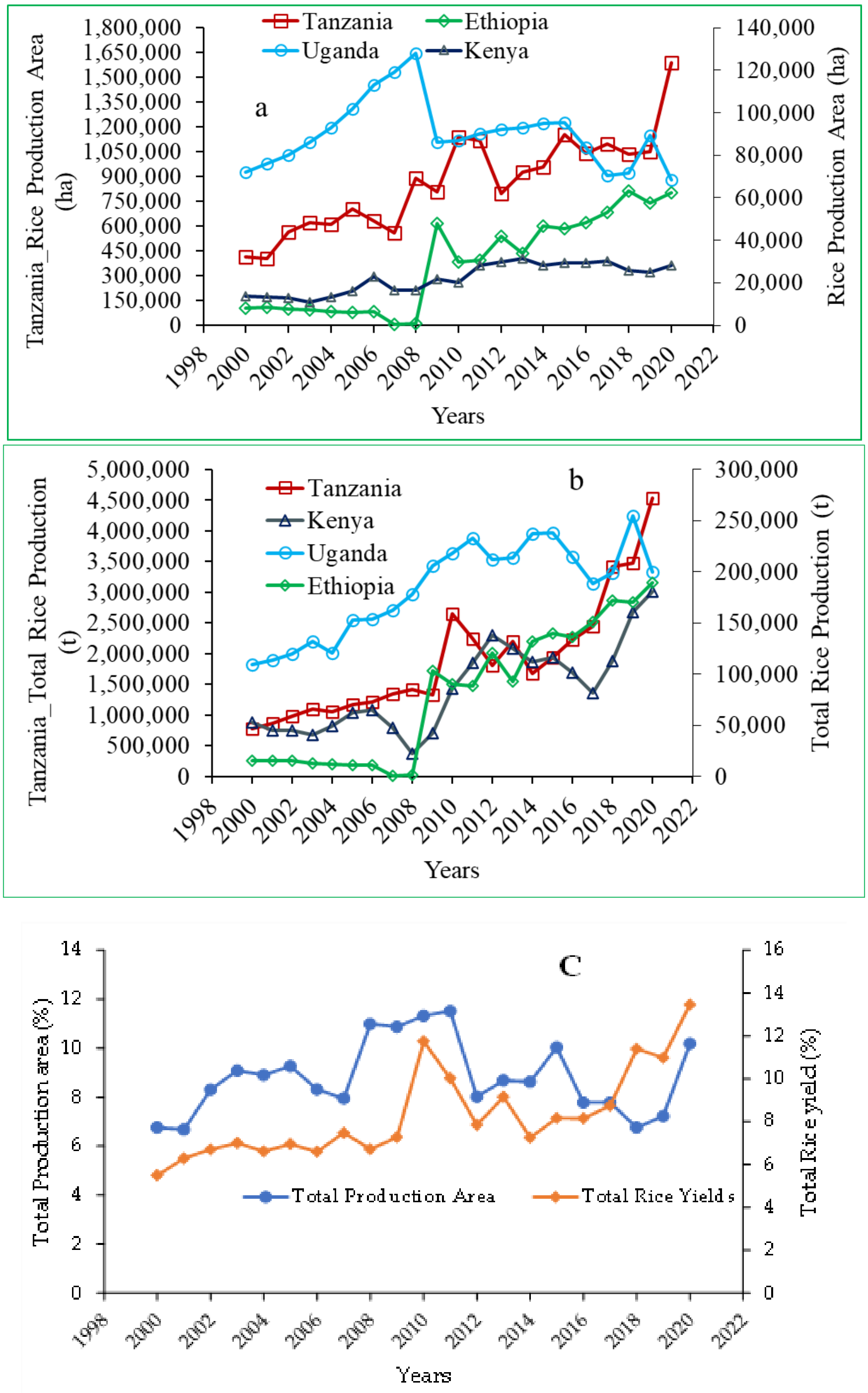


Figure 2. 4: Comparative changes in total rice production from 2000 to 2020: a) area (ha), b) production quantity (T), and c) as a percentage of the total rice production in Africa

Due to the recent rising gap between production and consumption, many EA countries are becoming increasingly dependent on rice imports (Table 2.2). Farmers use various rice varieties, such as Nerica4, Supa, Kaiso, Nerica 1&10, Sindano, and Superica in Uganda and Nerica A-6, NericaA-15, Hibire (IRGA370-38-1-1F-B1-1), and Hiddesa in Ethiopia (Belayneh and Tekle 2017). Two prominent varieties are grown in Uganda (Nerica 4 for upland and Supa for low land); in Kenya the main varieties are: MWUR 4, Dourado precoce, NERICA 4, NERICA 1, NERICA 10, NERICA 11 and NERICA 2 (Al-Imran et al., 2021). Paddy production represents > 65% of total rice production in EA.

Table 2. 2: Areas equipped with irrigation, under irrigation, and potential irrigated areas in the four East African nations from 1965 to 2010.

Country	Year	AEI (1000 ha)	AEI-AI (1000 ha)	TAWMA[**] (1000 ha)	Percentage, AEI-Ip (%)	Percentange, PAIL-Ip (%)
Uganda	1965	3.0	-	-	3.3	-
	1975	4.0	-	-	4.4	-
	1985	9.0	-	-	10.0	-
	1987	9.0	-	9.1	10.0	-
	1995	9.0	-	-	10.0	-
	1998	-	5.9	58.9	-	6.6
	2005	9.0	-	-	10.0	-
	2008	-	7.0	-	-	7.8
	2012	11.1	10.6	64.5	12.4	11.8
	2013	-	10.6	-	-	11.8
Ethiopia	2001	289.6	-	289.6	10.7	-
	2002	-	161.8	-	-	6.0
	2006	-	-	-	-	-
Tanzania	1965	-	28.0	-	-	1.3
	1975	52.0	-	-	2.4	-
	1985	127.0	-	135.2	6.0	-
	1983	-	-	150.0	-	-
	1995	150.0	-	-	7.0	-
	2002	-	-	184.0	-	-
	2005	184.0	-	-	8.6	-
Kenya	1965	14.0	-	-	4.0	-
	1975	40.0	20.9	-	11.3	5.9
	1983	-	30.5	-	-	8.6
	1985	42.0	-	-	11.9	-
	1990	-	51.4	-	-	14.6
	1992	66.6	52.8-66.6	73.03	18.9	15.0-18.9
	1995	70.0	79.0	-	19.8	22.4
	1998	-	84.4	-	-	23.9
	2002	-	91.4	-	-	-
	2003	103.0	97.2	109.6	29.2	27.5
	2005	103.0	-	-	29.2	-
	2008	-	106.6	-	-	30.2
	2010	-	-	150.6	-	-

Source: FAO AQUASTAT database; Nakawuka, et al., 2017; Droogers et al., 2011; Mati, 2008; Ngigi, 2002; Tafesse, 2003. AEI is area equipped for irrigation, AEI-AI is area equipped for irrigation and actually irrigated, TAWMA is total agricultural water managed area, AEI-Ip is area equipped for irrigation as a percentage of irrigation potential land, and PAIL-Ip is actually irrigated land to irrigation potential land.

[**] *In addition to areas equipped for irrigation, there are areas without irrigation facilities where water is managed informally since supply is not reliable and control is limited. These areas include cultivated wetlands, spate irrigation areas, flood recession cropping areas and inland valley bottoms. The total agricultural water managed area is the sum of the total area equipped for irrigation and areas with forms of informally managed water.*

Despite increases in rice production and yields in EA (Fig. 2.2b), water availability remains the primary limiting factor in semiarid regions (Barron *et al.,* 2003). Limited irrigation development and water management knowledge lends agricultural systems vulnerable to rainfall variability and dry spells even during rainy seasons (Mupangwa *et al.,* 2006). As such, production and yield from rainfed agricultural systems has been low; for upland rice, this is caused by uneven distribution of the rainfall across the production seasons in different areas (Barron *et al.* 2003). Additionally, water availability, inefficient fertilizer use, and unsustainable subsistence and continuous farming has depleted soil nutrients, contributing to declining yields (Sanchez *et al.,* 1997). Similarly, increases in drought response to temperature variations can limit rice production if these exceed optimum ranges that induce moisture deficits (Liu *et al.* 2008). Rice, both paddy and rain-fed, has an optimum growing temperature of 25°C, and temperature increases of 1°C above this optimum can cause a 10% yield reduction (Ghadirnezhad et al., 2014).

Considering the large quantity of fresh water required for rice production and rice trade in EA and other regions, exporting countries are trading water that is virtually embedded in exported products. This water that is embodied in the production and trade of rice is referred to as 'virtual water' (VW) (Allan, 1998). Additionally, water footprint (WF), a closely linked concept to VW, is an indicator of water use for all goods and services consumed per capita or on a national basis (Hoekstra, 2003). VW is a multidimensional indicator that specifies the volume of water consumed, water source, and pollutants, and is composed of three components: green, blue, and grey water footprint (Karthikeyan, 2020).

Table 2. 3: Comparative rice export and imports of East African countries for ten years.

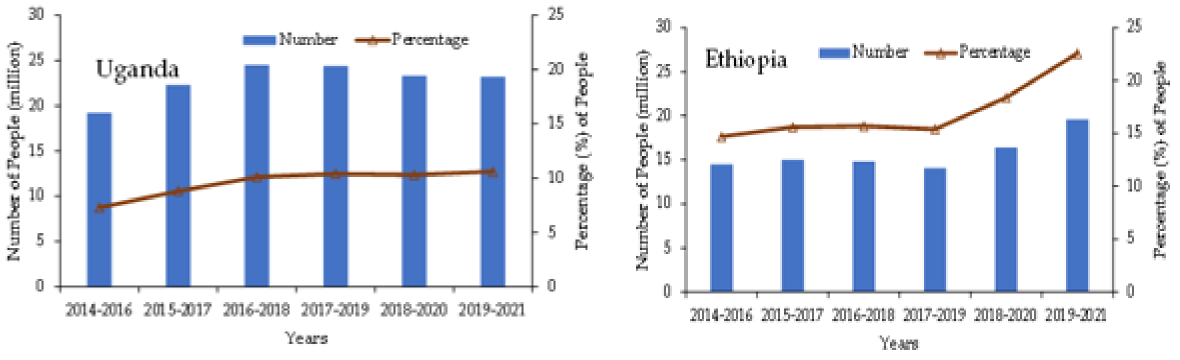
Country	Item Category	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ethiopia	Export (Tons)	0	8	30	240	1	3	0	0	72	0
	Export (1000$)	0	4	15	11	1	2	0	0	22	0
	Import (Tons)	41,356	92,567	116,958	139,789	204,524	221,466	231,582	388,793	285,476	70,769
	Import (1000$)	25,275	50,912	72,000	88,172	138,066	124,875	127,650	184,345	114,115	34,494
Kenya	Export (Tons)	621	923	520	89	43	13	108	350	496	134
	Export (1000$)	521	500	595	93	51	11	61	712	97	69
	Import (Tons)	283,017	437,744	374,562	595,970	490,000	650,000	585,360	582,404	600,502	582,130
	Import (1000$)	156,408	200,559	146,344	300,007	187,884	228,279	243,779	245,594	242,398	240,306
Uganda	Export (Tons)	17,592	22,146	31,183	16,775	16,981	8,998	12,197	5,189	18,852	21,206
	Export (1000$)	8,548	13,385	17,733	7,983	7,096	4,051	6,794	2,766	9,887	11,148
	Import (Tons)	44,123	45,106	52,114	65,385	27,732	31,714	33,175	49,257	75,396	237,767
	Import (1000$)	16,979	20,878	25,237	26,750	11,399	12,044	18,748	18,970	35,984	83,812
Tanzania	Export (Tons)	24,983	5,836	21,283	8,837	964	1,069	243	15,518	69,695	299,688
	Export (1000$)	10,764	2,326	10,159	2,551	332	308	75	2,491	32,207	128,100
	Import (Tons)	50,300	170,190	229,600	3,513	25,559	742	857	1,553	83	347
	Import (1000$)	23,800	87,200	113,000	1,534	8,139	597	477	1,068	19	156

Rice import and export data for 10 years was obtained from the Food and Agriculture Organization (FAO) database (https://www.fao.org/faostat/en/). EA imports a substantial amount of rice (> 500,000 tons annually) from Asia valued at approximately USD 500 million according to the Eastern African Grain Council (EAGC) (Kilimo Trust, 2018). Import and export statistics (Table 4) indicate that Tanzania is the largest producer and consumer of rice among the four EA countries with an annual consumption of 2,048,000 MT, followed by Kenya (370,000 MT), and Uganda (350,000 MT) (Kilimo Trust, 2018).

Rice production systems remain a growing sector in EA. Nevertheless, there are several environmental concerns, including: 1) how to fit rice production into farming systems because most paddies are in wetlands; 2) negative impacts of chemical use and disease arising from fertilizer and agrochemical applications; 3) disposal of rice wastes; 4) indiscriminate clearing of forests and wetlands for rice production; and 5) greenhouse gas emissions (e.g., methane) from paddy fields (Odogola, 2006; Zhang et al., 2011; Minamikawa et al., 2006).

2.1.4 Food Security-Population-Poverty Nexus in EA

East Africa is the world's most food-insecure region (IPC, 2020). Although there has been great improvement in global agricultural productivity and food security in recent years, the region has not followed this trend. Studies show that food insecurity has risen since 2014 (Figure 2.5). The region generally comprises one-third of the world's undernourished population and is the only area where agricultural productivity per capita has been falling for the past 30 years (De Carvalho, et al. 2020). EA has significant untapped potential to achieve food self-sufficiency and increase food exports if it ceases to rely on food imports and instead intensifies farming activities (Onwujekwe and Ezemba, 2021). Currently, more than 70 million people in the region are undernourished (Figure 1.4), including > 15% of the total population in Ethiopia and Tanzania and 10 and 14% in Uganda and Kenya, respectively, severely food insecure by 2021 (Figure 2.5).



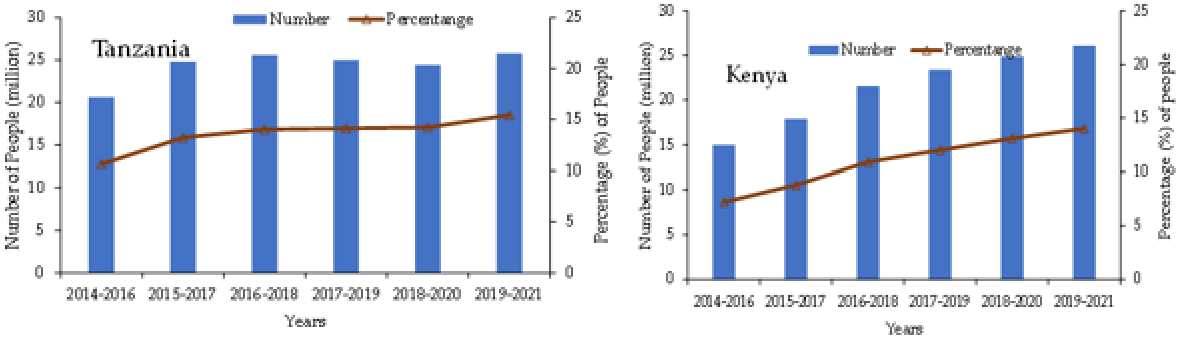


Figure 2. 5: Prevalence of food insecure population in East Africa from 2014 to 2021.

The causes of food insecurity in the region are complex and multidimensional. These are linked to several factors: drought, environmental degradation, poverty, conflict, land fragmentation, declining soil fertility, poor access to basic social services, and inadequacy of public policies (Abdullah et al., 2019; Oluoko-Odingo, 2011; Funk et al., 2008; Devereux, 2009). Food supplies in many parts of the developing world are locally derived, with much of this produced by rain-fed agriculture (Funk et al., 2008). Therefore, changes in rainfall and temperature directly influence food supplies, cause water shortages, and heat stress limits crop growth, development, and yields (Prasad and Staggenborg, 2008).

Smallholder farmers, including herders and fishers, comprise the largest percentage of the region's poor inhabitants (Salami et al., 2010). Moreover, the largest segment includes those belonging to indigenous populations living in rural areas and surviving on subsistence farming. These farmers depend largely on rain-fed agriculture, particularly susceptible to droughts, floods, and shifts in markets and prices. Hence, strategies to reduce rural poverty will rely mainly on improved water management in agriculture, as noted in Ethiopia (Hagos et al., 2012).

Additionally, the poverty situation in the region is exacerbated by concurrent issues, such as recent desert locust invasions, weather-related shocks in Kenya, and the refugee influx and weather extremes in Uganda (FSIN, 2020). The World Bank (2020b) noted that the 2016/2017 drought in Uganda increased the poverty rate by 1.7% from levels in 2013 to 21.4% in 2016, and multidimensional poverty incidence was estimated at 60% in 2016. In Kenya, the proportion of people living below the poverty line was estimated at 36% in 2015/16, reaching 70% in rural areas (Monica et al., 2020). Approximately 1.3 million people in Kenya face acute food insecurity and need assistance as of late 2019 (USAID, 2020).

The region is experiencing high population growth at the rate of 1.1 million people annually (Figure 2.6), with most people living in rural areas. Many youths are now moving to cities in search of employment opportunities (Buhaung and Urdal, 2013). Annual population growth projections vary from 1.089 to 4.767 million. Population in Uganda is projected to surpass Kenya by 2050 (Figure 2.6). These population increases exert pressure on water resources and increase food demand, therefore food imports. Agriculture remains integral to the future of EA's industrialization, poverty reduction, employment opportunities, and overall food security (Ogola, 2013). While food security is being affected by climate change, most importantly, it depends on economic growth, changes in trade flows, and food aid policies (Nicol, et al., 2015).

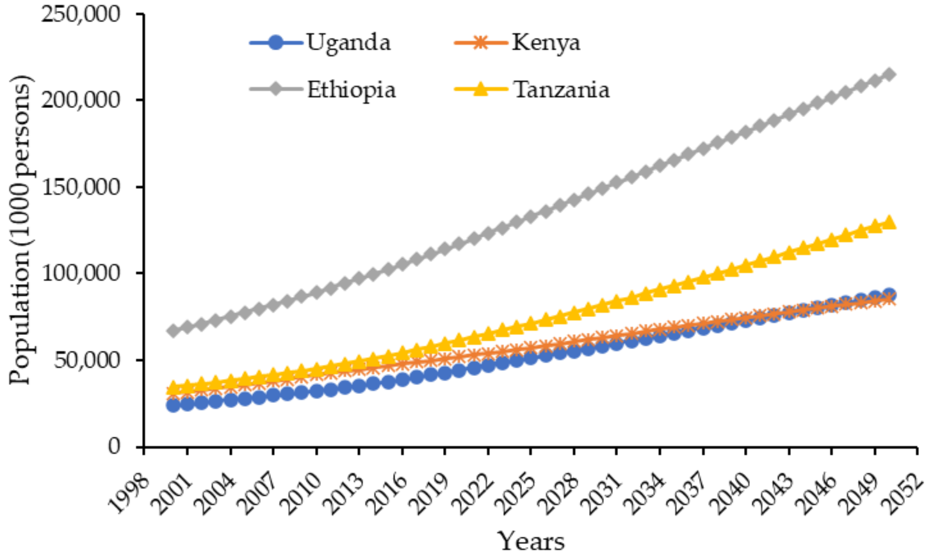


Figure 2. 6: Population growth projections and estimates of East Africa: Uganda, Ethiopia, Kenya, and Tanzania, from 2000-2050.

2.1.5 Climate Change Impacts on Rice Production

Food insecurity is a global challenge, and many countries struggle to provide sufficient and affordable food for their families. This is a result of population growth, urbanization, climate, and other factors (Godfray et al., 2010; Brown and Funk, 2008). Climate is denoted by either climate variability or climate change, i.e., short-term, or long-term variations ranging from decades to millennia (Dananjaya et al., 2022). Although agriculture is likely the most vulnerable sector to climate change because of potential impacts on food production, climate effects are not evenly distributed (Enete and Amusa, 2016). Developing regions such as Africa are severely affected by climate change due to low adaptive capacities and slow recovery trajectories (Lemi & Hailu, 2019; Haile et al., 2019). The impacts of climate change on rice production have been studied at regional and global scales (Mall and Aggarwal, 2002; Zhang and Tao, 2013; Chen et al., 2011).

Changes in precipitation and temperature directly affect crop productivity, but severe climatic events, such as droughts, are projected to have negative impacts on the crop yield in Sub-Saharan Africa (SSA) and Asia, contributing to rice yield reductions (Ayugi et al., 2022; Haile et al., 2019; Gornall et al., 2010). Climate variability in most parts of Africa occurs on seasonal and decadal time scales and the region experiences frequent droughts and floods (Dananjaya et al., 2022; Ayugi et al., 2022). As a result, these climate threats are major causes of hunger, malnutrition, poverty, and obstacles to social and economic development (Ayugi et al., 2022).

Additionally, about 70 million people are exposed to drought risk in EA. Climate change greatly contributes to the precipitation deficit which has worsened since November 2021. The cumulative precipitation deficit from July 2020 to June 2022 compared to the reference period 1981 to 2020 is severe across large regions in EA (Toreti, at al., 2022). The driest regions in southeastern Ethiopia and eastern Kenya have deficit values up to about 50% based on CHIRPS data and even higher (up to about 70%) based on ECMWF ERA5 reanalysis. Spatial patterns are similar between the two datasets with the main differences in: northern Ethiopia, southern Uganda, and northern Tanzania (deficit for ERA5, surplus for CHIRPS). The magnitude of the deficit appears uniformly more severe for ERA5 data (Fig. 1.6).

Whereas long-term precipitation predictions are uncertain, several studies show declining rainfall between March and June and rising sea-surface temperature along coastal EA (Williams and Funk., 2011; Funk et al., 2005). These temperature increases enhance convection over the tropical Indian Ocean causing dry air to descend over EA, suppressing convection since 1980 and decreasing precipitation. In addition, rising surface temperatures in the Indian Ocean are linked to greenhouse gas emissions (Funk et al., 2005; Williams and Funk, 2011; Funk et al., 2010), which are likely to continue and warm the south-central Indian Ocean, prolonging the drought trend. This will contribute to water shortages, affecting rice production in EA (Williams and Funk, 2011; Funk et al., 2011). More drought events are being reported as confirmed by the Drought Indicator (CDI) and IGAD Climate Prediction & Applications Centre-ICPAC (https://droughtwatch.icpac.net/mapviewer/) of EA, indicating drought stress related to rainfall deficits over large areas of south and east Ethiopia, Uganda, coastal regions of Kenya, and some areas in Tanzania (Fig. 1.6). It is predicted that drought and precipitation deficits will persist for more than 5 years in most of EA (Figure 1.6). If this occurs, irrigated and rainfed crop production will decline, especially rice production, because it requires much water.

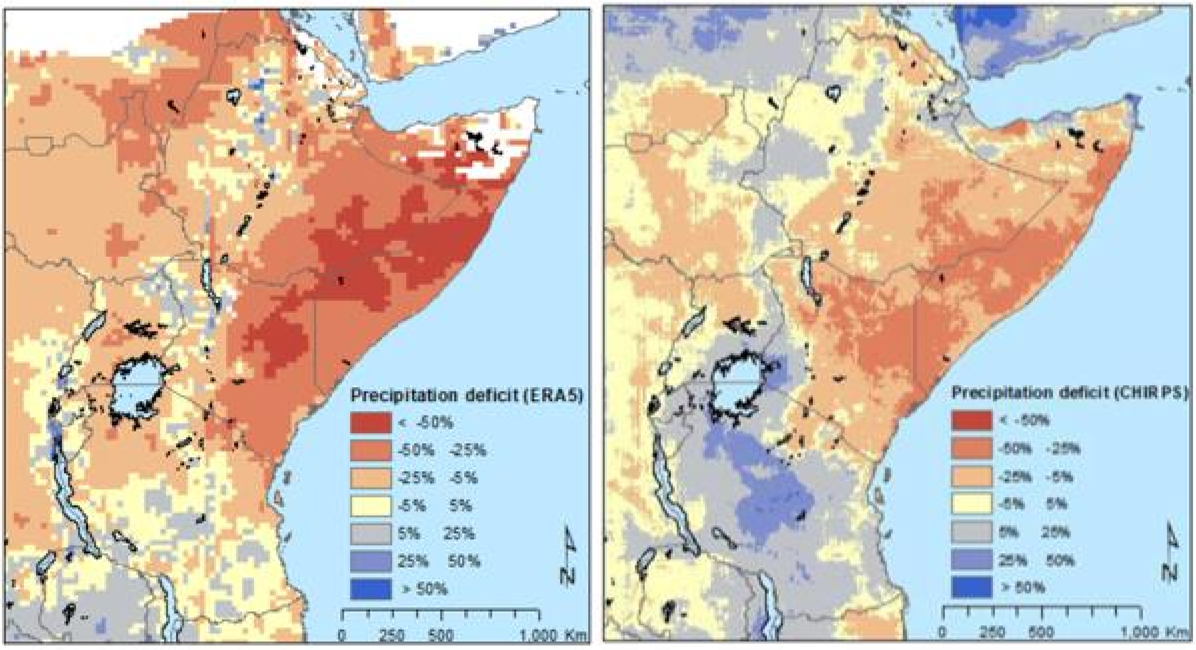


Figure 2. 7: Precipitation deficit % compared to the reference period (1981-2020) for the period July 2020 to June 2022 according to the ECMWF ERA5 reanalysis (left panel) and CHIRPS dataset (right panel). Desert areas (based on climatology) and water bodies are masked in ECMWF ERA5 reanalysis. Source: Toreti, at al., 2022

2.2 Current Water Management and Conservation Practices

In the design of rice paddy fields, agricultural water management and conservation should be a priority for effective water utilization due to climate change limiting water resources (Suzuki, 1994). Several factors threaten rice productivity in EA prompting studies to improve water technologies to increase rice yield in inland valleys and upland areas. Supplemental irrigation and soil conservation practices such as mulching for upland cultivation are being implemented at small scales (Dossou-Yovoa, et al., 2022). Supplemental irrigation during dry spells of erratic rainy seasons can enhance rice productivity. In Uganda, 20 mm of supplemental sprinkler irrigation every five days during dry windows starting from the rice panicle initiation stage increased yields by 37%, fertilizer use efficiency by 54%, and profitability of rice cultivation by 32% (Onaga et al., 2020).

Among the water management approaches advocated to enhance rice production and save water, alternate wetting and drying (AWD) irrigation is the most promising method (Bwire et al. 2022a) in addition to system of rice intensification (SRI). This and other water management and conservation methods are summarized in Table 2.3. However, little research and innovative practices related to climate and optimal water use, agronomic and economic performance, and determinants of climate-smart water management adoption for paddy and upland rice production have been applied in the region. Most these climate-smart water management techniques are at micro-scale research level in EA while SRI is being piloted in Oluch irrigation scheme in Kenya (ouma et al., 2024)

Table 2. 4: Summary of water management technologies for rice production in East Africa.

Technologies	Features	Applications	References
Contour bunds and water retention dikes	Small dikes around the rice field. Small dikes made of soil material built in the valley bottom following contour lines. Dikes constructed perpendicularly across the valley bottom	Paddy, upland	Hatibu and Mahoo, 1999; Pretty et al., 2003
Supplemental irrigation	Addition of limited amounts of water to improve and stabilize yields of rain-fed crops when rainfall fails to provide sufficient moisture for normal plant growth.	Rain-fed, Upland	Onaga et al., 2020
Conservation agriculture, limited tillage, zero tillage	Reduced or no-tillage of the soil in the field or mulch of crop residues and diversified crop rotation.	Upland	Adamtie, 2021; Hatibu and Mahoo, 1999; Mkonda and He, 2017; Anderson et al., 2015
System of rice intensification	Cultivating rice with organic manure if possible, starting with young seedlings planted and widely spaced in a square pattern, including alternate wetting and irrigation	Paddy	Katambara et al. 2013; Too et al., 2019; Kahimba et al., 2014; Materu et al., 2018
Alternate wetting and drying irrigation (AWD)	Use of field water tubes (piezometers) or tensiometers to monitor water levels in rice fields and irrigate when soil water drops below a threshold or a soil potential.	Paddy	Blango et al., 2019; Kahimba et al., 2013

Additionally, water conservation is an important component of water management, and many studies have described factors affecting the adoption of soil water conservation measures (SWC). The dimensions of farms and land ownership are important components associated with adopting conservation measures, especially for upland rice cultivation (Jara-Rojas et al., 2012). For example, research on social and economic factors affecting the adoption of SWC practices in the western Uzambara Mountains of Tanzania indicates that age, gender (especially women), educational status of the heads of families, and land ownership have significant positive effects (Teng et al. 2004). Alternatively, challenges associated with adopting SWC measures are attributed to the lack of farmers' awareness of soil erosion and poor understanding of financial benefits from SWC measures (Tenge et al. 2004).

2.3 Adoption of AWD Technology: Challenges, Limitations and Opportunities

Policies for promoting and disseminating AWD was introduced in several Asian countries due to its benefits EA. For example, safe-AWD was proposed in northwest Bangladesh in 2004, a major rice-growing area that experiences water scarcity due to rapid expansion of groundwater use for irrigation (Pandey et al., 2020). However, despite AWD's potential water saving and economic impacts, limited data exist on the integration and adoption of AWD by farmers and in large irrigation systems, although missing in EA.

Additionally, AWD has been assumed to promote growth of weeds that require additional labor, although recent research indicates no weed increase and additional labor with AWD (Rejesus et al., 2011). Similarly, unreliable water and energy supplies are potential obstacles for adopting AWD because it requires well-tuned irrigation intervals and management measures. The technology requires more time for field inspection and manual measurements of WL in observation tubes. Therefore, some uncertainty arises due to the mismatch between the actual time of WL decline in tubes and measured WL, as farmers do not know when the water has dropped to critical levels in the tubes.

Rice cultivars with shallow roots will have a more significant proportion of their root system in aerobic conditions than those with deep rooting. Therefore, the architecture of root system compared to the timing and magnitude of soil matric potential and soil redox fluctuations can significantly affect water regimes in AWD practice, thus affecting the availability and nutrient uptake of phosphorous (Adam et al., 2013; Kirk 2004). Cadmium (Cd) accumulation in grains is debatable for paddy rice grown in more aerobic conditions (Arao et al., 2009). However, some research has shown that mild and severe paddy soil drying can reduce grain accumulation of Cd (Yang et al., 2009). Therefore, in promoting and adopting AWD programs, reducing Cd accumulation in rice grains should be prioritized (Meharg et al., 2013).

Optimizing AWD irrigation requires addressing several questions: "To what extent is the root system of the rice cultivars suitable to the temporal and spatial variation of soil moisture and oxygen considering paddy soil type, structure, and characteristics?". Similarly, design criteria for the number and distance between observation water tubes needs to be evaluated because one observation tube per paddy may not fully represent WL variation in the paddy field. Integrating this WL monitoring design into large irrigation schemes necessitates solving the first question due to the impact of AWD on hydrological properties in paddy soils. Such technologies improve water management in a changing climate. Therefore, governments in EA should develop workable policies that enhance adopting such appropriate technologies given changing climatic conditions affecting paddy rice farming, training.

2.4 Summary

Decreasing water availability for irrigated agriculture due to climate change is threatening paddy rice production in the region. Any water stress on paddy rice will likely decrease rice yield and quality. Water saving techniques, such as AWD, are unique management practices for paddy rice catchments that change hydrological properties of the paddy fields; however, such changes have been little studied in the region. The application of AWD technology among farmers requires technical knowledge.

Therefore, there is potential for promotion of AWD technology in the region though designing an integrated approach for adoption the technology to improve on water management, requires: 1) in-creased funding for research, pilot demonstration, and technology transfer of the AWD practice; 2) feasibility analysis of paddy rice catchments, ground water resources and integration in irrigation system design planning by engineers, administrators, and managers to implement the technology; 3) selection of champion farmers as visible examples, thereby promoting farmer to farmer learning approaches; and 4) develop partnership with stakeholders and AWD practitioners will facilitates information dissemination to more farmers (Palis et al., 2004). Improving emission trading, by designing AWD technology as climate smart practice based on a clean development mechanism (CDM) of the Kyoto protocol of 1997, will accelerate the adoption of the practice. Since the technology involves sustainable, efficient use of energy and natural resources, offering win-win options for climate and sustainable development, and economic benefit to farmers (Siopongco et al., 2013).

Chap. 3: AWD Regimes and Paddy Rice Experiments

3.1. Introduction

Water scarcity is becoming a bigger global concern. Additionally, irrigation agriculture uses over 70% of the world's fresh water and the demand is expected to increase to meet future food security. Drought is becoming a serious global issue and crises in many countries contributing to water scarcity, drying of water sources such as lakes, rivers and seasonal streams and reducing irrigated rice yields (Hyunwoo et al., 2021). Rice is one of the most staple food crops critically important for food security to half of the world population where rice accounts for about 80 percent of their food consumption (Djaman et al., 2020; Pourgholam-Amiji et al., 2020). In addition, 114 countries grow rice, and more than 50 have an annual production of 100,000 tons of rice or more. Rice has been cultivated in more than 146.5 million hectares of the world agricultural lands (Gill et al., 2014; Lampayan et al., 2015) though the production is significantly affected by drought issues. Like in most sub-Saharan African countries, rice is one of the cereal crops grown in Uganda mostly by smallholder farmers for income with few large schemes and total production of 350,000 MT annually (upland and paddy) (Akongo et al., 2017).

Paddy rice cultivation has been carried out using the traditional continuous flooding (CF) irrigation which provides enough water supply and weed management by keeping root zones anaerobic conditions. The anaerobic conditions in paddy result from oxygen restrictions in the soil due to long duration of pond water in the field after flooding. The same conditions were observed with pot experiments in CF mostly at vegetative to reproductive stages. Traditional continuous flooding is being practiced by smallholder farmers in Uganda who faces several challenges such as underdeveloped irrigation and water structures, poor water management and drying of water sources due to drought (Bwire et al., 2022b). In contrast, the country's rainfall pattern can support two rice seasons in the year, with precipitation of 750 mm/year in the driest areas in the northeast to 1,500 mm/year in the high rainfall areas of Northern, Eastern, and Western parts of the country (Hong et al., 2021). This is becoming impossible due to climate change since rice cultivation under the traditional system demands higher water input than the other cereal crops (Datta et al., 2017).

On the other hand, the water demand is increasing for both domestic and industrial use. This contributes to reductions in the water availability for agriculture purposes and water conflicts among water users and among farmers which cannot be avoided. Additionally, surface and underground water resources are shrinking which is posing a threat to the future of rice production (Faroog et al., 2009). The current challenge for paddy rice cultivators is to increase the water productivity by growing rice with less water, which is possible [12-13]. Promotion and adoption of effective water use-saving techniques for rice production to reduce water use in the agricultural sector without affecting the yields (Carrijo et al., 2017), with climate change being inevitable, is necessary. Alternate wetting and drying (AWD) irrigation is one of the water-saving techniques widely being promoted for rice cultivation (Shu et al., 2014). It has been considered as a climate-smart water-saving technique being practiced in many Asian countries such as China, Bangladesh, India, and Vietnam (Yang et al., 2007; Zhang et al., 2009).

The AWD practice was developed by International Rice Research Institute (IRRI), in the 1970s [19-20]. The practice comprises of three basic elements: 1) shallow flooding for the first 2 or 3 weeks after seeding or transplanting to recover seedlings from transplanting shock, and to suppress weed emergence [21], 2) ponding layer of 2−5 cm of standing water from panicle initiation (PI) to the end of flowering because this duration is very sensitive to any water stress, and 3) AWD cycle through the rest of crop growth periods [22]. The AWD system ensures supply of the physiological water demand [23] of rice by controlling water supply and reducing the total water input. In AWD, fields are subjected to periodic cycles of wetting and drying of soil, which is closely linked with the number of factors such as the soil texture, soil water potential, plant water status, and soil hydraulic conductivity [24]. The field water observation tube developed by IRRI can be used to monitor the water level beneath the soil surface. Half perforated field water tubes can be made using bamboo, PVC pipe, tin cans, or even plastic bottles with a diameter of 10−20 cm and based on the materials availability. Using perforated field water tubes enables farmers to monitor the water table easily. Water is first applied to a depth of around 5 cm, and then the farmers wait until the perched water table falls to a certain limit beneath the soil surface due to, percolation, drainage, and evapotranspiration. The fields are then re-irrigated when field water level (FWL) reaches 15 cm or less (in water pipes) below the soil surface which is referred as ‘’safe AWD” [25]. Threshold level at “safe AWD” increases or maintains the yield with water-saving of 15–30 %, as at this threshold level, roots of plants are still able to acquire sufficient water from the saturated soil and perched groundwater for growth and development [23]. Farmers are encouraged to implement the “safe AWD” technique during vegetative growth (tillering to PI) and then at the grain-filling stage [26].

Several studies have reported that compared to traditional continuously flooding conditions, AWD can maintain or even increase grain yield [16-18]. On the contrary that yield penalty is commonly observed under AWD compared with traditional continuous flooding [19-20]. Generally, Generally, AWD increased water productivity with respect to total water input because the yield reduction was smaller compared to the amount of water saved [17]. AWD can save water while maintaining rice yields, but in some countries its adoption by farmers remains limited due to lack of knowledge and skills, perception due to the key knowledge gaps in AWD practice which include its effect on early vegetative vigor, unknown relationship with yield and water use efficiency based on different local cultivars used by smallholder farmers, and the socio- economic factors influencing AWD irrigation scheduling which involves frequent field monitoring [27]. Additionally, there are two primary methods to further increase rice yield. The first is to increase the harvest index (HI) when the biological yield is certain [28]. The second is to increase the biological yield under the condition of a certain HI. The HI is the ratio of the crop marketable yield to the biological yield. This concept was first proposed by the former Soviet scholar Niki Porovich in 1954 [29]. Currently, a series of studies have been conducted to increase yields by improving HI [29]. The research by Mai *et al*., [31] showed that the cultivation method of sowing effectively improved the rice HI. It is important to note that one aspect of field research such as experimental studies with crop cultivation should be carried out at least two or more seasons [32].

One of the challenges is defining the AWD practice since the water application is based on either soil water potential or field water level, however, there is three categories of AWD conditions: safe-AWD, mild/moderate-AWD, and severe-AWD approach. Safe AWD is defined by field water level when the water level reaches less or 15 cm depth below the soil surface [23], while Mild AWD condition is when the water level reaches after 15 cm to 20 cm and severe AWD when FWL reaches 25 cm. Safe AWD is considered appropriate since it has minimal effect on yield. Additionally, the AWD practice by matric potential is defined when matric potential head in the rootzone reaches −20 kPa or less for safe AWD, −45 kPa for mild AWD or −70 kPa for severe AWD [14]. This relationship varies depending on the soil type, soil hydraulic conductivity, environmental factors and farmers' experience. Whereas IRRI recommends water application with AWD practice after two or three weeks, after transplanting or direct seeding [19-20], then continuous flooding at panicle initiation to end of flowering since rice is sensitive to any water stress [22]. However, in this research, water regimes in AWD conditions were set under safe AWD (less or 15 cm depth), and the water regime was defined when FWL reached 5, 10 and 15 cm depth below soil surface to evaluate safe AWD. The water application after the start of water regimes was carried out throughout the whole cultivation period, which is opposed to the IRRI recommendations. The effect of water regimes with safe AWD practice throughout the whole cultivation period has not been studied. Similarly, if promoted in Uganda, the safe AWD practice can enhance water use and management since the government, through agricultural and rice sector development and investment plans, is rehabilitating irrigation schemes to increase paddy cultivation [8].

This chapter examines the effect of AWD regimes on water productivity, rice yield, dry matter accumulation, and HI under different safe AWD regimes throughout the whole season. Therefore, the objectives of this research are (1) to apply and evaluate FWL of safe AWD practice to determine the appropriate observation depth leading to optimum water use, and (2) to evaluate water productivity, water saving, and harvest indexes under the different safe AWD regimes. The findings of the present study provide useful information to farmers carrying out paddy rice cultivation in countries facing water shortages due to climate change and drought. The study also provides scientific knowledge on the application of safe AWD practice throughout the whole season.

3.2. Materials and Methods

3.2.1. Experimental Design and Site Description

The study was carried out for three cultivation seasons: spring, February 2021 to May 2021, June 2021 to September 2021, and from December 2021 to March 2022 in glass greenhouses at Tokyo University of Agriculture and Technology (TUAT), Fuchu described by the Longitude and Latitude of 139.4787° E, 35.6840° N, respectively and 67 m above sea level. The temperature inside the glass greenhouse was set between 20^0C to 30^0C. Temperature variation in the phytotron was controlled with an air conditioner. The experiments were carried out in 1/5000-a Wagner pots (4.0 L, 24 cm in diameter, 30 cm in height) with compared air-dried soils from paddy field, taken from Field Science Center, TUAT, Honmachi after sieving it from a 4-mm sieve to maintain the field conditions including puddling. The site has clay loam soils as defined by the United States Department of Agriculture (USDA) of soil texture classification with a pH of 6.8, total carbon of 42.9 g/kg, total nitrogen of 3.4 g/kg, and available phosphorus of 0.46 g/kg.

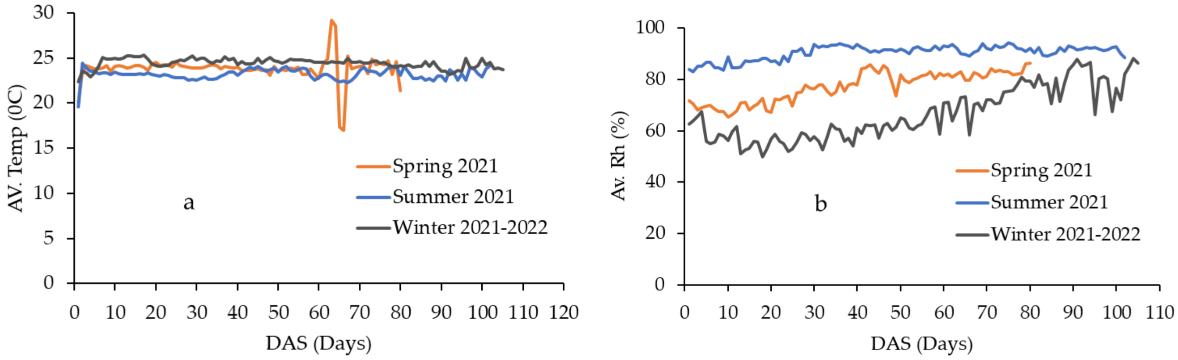
Meteorological data such as temperature, relative humidity, and solar radiation were measured and recorded from a meteorological station placed within the glass greenhouse (Figure 3.2). Additionally, relative humidity and temperature sensors were placed in phytotron to measure and record the ambient temperature and relative humidity continuously at the 10 minutes interval with an automatic T–RH data logger (LR5001, Hioki, Japan) placed at 1 m above crop heights (Figure 3b). Hioki LR5001 compact 1 or 2-channel data loggers has a

60,000 data set/channel memory to measure temperature, humidity, voltage or instrumentation signals. The LR5001 logs temperature and humidity over 2 channels in as fast as 1 second intervals. It has measurement range, temperature: -40.0°C to 85.0°C, humidity: 0 to 100% RH at sensor environment. The accuracy: Temperature ±0.5 °C (main unit + sensor accuracy, at 0.0 to 35.0 °C) and humidity: ±5 % rh (main unit + temperature / humidity sensor LR950x combination, at 20 to 30 °C / 10 to 50 % rh).

Diurnal variation of the average, temperature, relative humidity, and solar radiation during the cultivation experiment are plotted in Figure 3.1.

Figure 3. 1: Meteorological measurements in the Phytotron

Where a) ATMOS41 all in one weather station, and b) Hioki LR5001-TRh data logger and sensor.



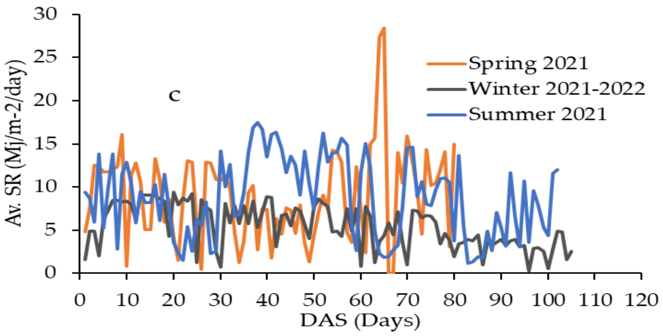


Figure 3. 2: Diurnal variation of average temperature (a), relative humidity (b) and solar radiation (c) conditions in phytotron in season 1, 2 and 3.

Where Av. Temp.; average temperature, Av. Rh (%); average relative humidity and Av. SR; average solar radiation, SR; solar radiation and data obtained from the ATMOSI 41 in the phytotron.

3.2.2. Irrigation Regimes

The pots in the closed system–phytotron were arranged in a randomized block design with four treatments and three replications as described below:

Continuous flooding Irrigation (CF) as a control treatment was applied during the whole rice-growing period, in which water was applied when ponded water dropped to a zero level on the soil surface. The water application to the pots was always measured and applied by a watering can.

Alternate wetting and drying (AWD) conditions described as AWD5, AWD10 & AWD15 correspond to the irrigation period when water table in the observation tube reaches 5, 10 and 15 cm soil depth after the disappearance of surface ponding water, respectively. All the AWD conditions fall under the safe approach recommended by the international rice research institute (IRRI) not to cause yield decline (Richards and Sander, 2014). However, in this research, water was applied through the whole cultivation period in AWD regimes after the start of irrigation treatments which is opposed to the IRRI recommendations. The AWD wetting and drying conditions is shown in the schematic illustration (Figure3.3).

All pots were of the same size of 24-cm diameter and 30-cm height with a closed bottom. The total number of experimental pots were 12 placed in two glass greenhouses of the same condition, as shown in Figure 3.3. Paddy soil was collected from the experimental paddy field of TUAT and sieved with a 4-mm sieve before packed in the pots with the same dry density of the field soil to maintain the field conditions.

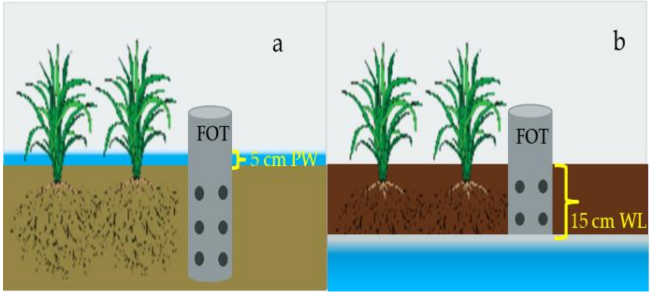


Figure 3. 3: Schematic illustration of alternate wetting and drying practice in pot expirement

Where a) wetting conditions and soil drying condition (b). FOT; Field observation tube, PW; ponded water, WL; water level.

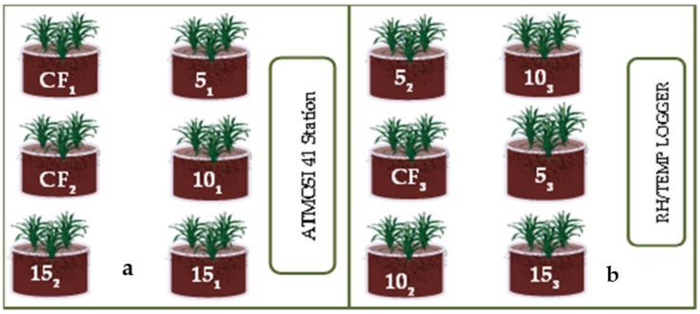


Figure 3. 4: Experimental design and treatments in Phytotron

Where (a) and (b) where CF is the control and 5, 10 & 15 are AWD 5, AWD 10 & AWD15 conditions, CF; continuous flooding irrigation, AWD; alternate wetting and drying irrigation practice. Each treatment has three replications.

3.2.3. Rice Cultivation and Field Parameters

Rice variety, Ikuhikari, a short Japanese grain and widely grown rice cultivar (Kobayashi et al., 2018), was directly seeded on Feb 12, 2021, for spring season, June 12, 2021, for summer season and December 14, 2021, for winter season. Water regimes in all seasons were applied between 17 to 30days after direct seeding (DAS). From direct seeding to harvest, average pot seasonal rice water consumption varied from 57 to 90 liters during spring period, 96 to 117 liters during summer period and 78 to 120 liters for winter period, depending on different water regimes. During each irrigation, a known amount of water was applied (measured with a graduated beaker) using a watering can. The stages of rice cultivation from direct seeding, fertilizer application, and irrigation application to harvest, are summarized in Table 1. Water application in all regimes was stopped 4 days prior to harvesting. The total number of days from direct seeding to harvest varied according to the cultivation period (Table 3).

Table 3. 1: Variation of rice cultivation from direct seeding to maturity

Stage	Direct Seeding	Start of Water Regimes	1st Fertilizer Application	2nd Fertilizer Application	Maturity Stage
DAS (Season 1)	3	33			89
DAS (Season 2)	3				100
DAS (Season 3)	1	17	30	64	105

3.2.4. Growth, Tillers, Leaf Area Index (LAI) and Yield Components

The crop height was measured on a weekly basis using a tape measure, and the number of tillers were counted manually in each treatment. The yield components (number of grain panicles, grain number, grain weight and brown/filled grains) were measured after harvest. The yield survey was performed by measuring rice grain number using rice counter and grain weight before and after dehusking. The rice pot was sampled with each treatment and the number of grains (mature and immature) were measured. Mature rice grains were separated by sieving to separate them from immature ones. The grain numbers were recorded, and the percentage of mature grains were obtained from the number of total rice grains.

Additionally leaf area index (LAI), defined as the total one-sided area of photosynthetic tissue per unit ground surface area (Watson, 1947) is vital component of assessing the crop canopy structure and modeling of energy balance. Several methods including direct methods, referred to as harvesting destructive methods have been applied in estimation of lAI index (Aschonitis et al., 2014). However, in this study LAI was estimated manually by measuring the leaf length (L) and width of the rice leaves from three water regimes: CF, AWD 5 and AWD 15 as representative for the experiment (Figure. 3.5). The leaf area (LA) and LAI were estimated from the equations (Zhang at al., 2018; Gao et al., 2023) below:

$$\text{LA} = \text{Leaf length (L)} \times \text{Leaf Width (W)} \times 0.75(\text{Correction factor}) \tag{3.1}$$

$$\text{LAI} = \frac{Sum\ of\ the\ leaf\ area\ of\ crops}{Surface\ area\ of\ the\ Pot} \tag{3.2}$$

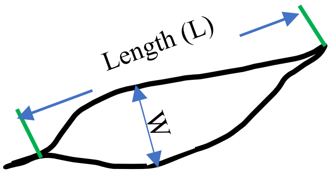


Figure 3. 5: Schematic illustration of the measurement of LA components of rice.

3.2.5. Harvest Indexes, Biomass Dry Matter Content and Water Productivity

The harvest index (HI) is one of the factors used to measure the difference between the potential and actual yield. For this research, HI was based on above-ground biomass and actual yields and estimated as below (Katharine et al., 2015).

$$\mathrm{HI} = {}^{\mathrm{Y}}\!/_{\mathrm{AGB}} \tag{3.3}$$

where Y is the yield (kg/ha) and AGB is the above ground biomass accumulation (kg/ha).

Additionally, the fresh leaves were cut and separated from the rice stem after harvest to obtain the fresh weight. The stems and leaves were further cut into small particles and oven dried for 72 hours at the temperature of 70^0C to avoid biomass burning. The total ratio of biomass dry matter content to fresh biomass was expressed as a percentage.

Likewise, water productivity is expressed as the total of irrigation water productivity (WP), and rainwater productivity (RWP) which are the total water (rain + irrigation) (Pascual and Wang, 2017), expressed in kg/m^3; Y is the grain yield expressed in kg/ha^1. In this research, the rice's WP was obtained by dividing the average yield on the average season irrigation water consumed per pot in each treatment during the whole cultivation growth period. WP is an important index for the evaluation of irrigation water management (Kijne et al., 2003).

$$\mathrm{W_p} = {}^{\mathrm{Y}}\!/_{\mathrm{I}} \tag{3.4}$$

where Y is the yield of rice (kg/ha), and I is the amount of irrigation water (m^3/ha).

3.2.6. Measurements of Soil Hydrological Conditions

Two hydrological conditions were measured, water level and soil water pressure heads. Water level at 5, 10 and 15 cm below the soil depth that defined AWD5, AWD10 and Awd15 respectively were measured using meter rule while the tensiometer, TORES 32 were installed at the same depth of 10cm to measure and record soil water pressure heads (Figure 3.6a) in different water regimes. Similarly drilling depth to install the TORE32 tensiometer (Figure 3.6b) in the pots was estimated basing on the depth of soil column using the equation below:

$$\text{Drilling depth} = \frac{Installation\ depth}{Sin\ \alpha} \tag{3.5}$$

Where α; installation angle at 45^0C and installation depth of 10 cm, due to pot and soil column

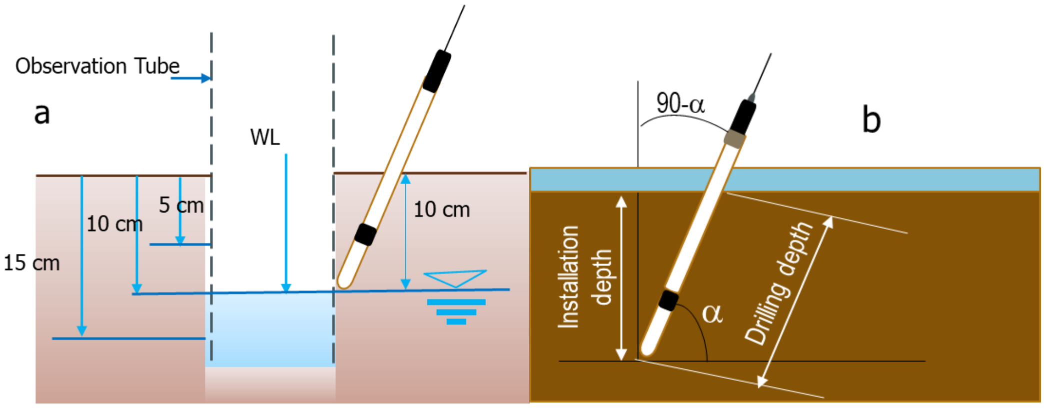


Figure 3. 6: Illustration measurement of water level (WL) and soil water pressure heads

3.2.7. Data Process and Analysis

The data analysis was of variance (ANOVA), and this was performed in Microsoft excel with comparative analysis using the Fisher man's pairwise comparison method (Williams and Abdi, 2010). The lowest significant difference (LSD) was obtained as below.

$$LSD = t_{v}, \alpha \sqrt{MS_{s(A)} \left(\frac{1}{S_{\alpha}} + \frac{1}{S_{\alpha^1}}\right)} \tag{3.6}$$

where α is the number of observations per treatment, $MSs_{(A)}$ is the mean square error within the group A, t is the t-statistics from the statistical t-distribution table, and v is the degree of freedom obtained from the same table.

To make the conclusion, the absolute value of the difference between means was compared with LSD. If the difference between means was found to be greater than the LSD, then it was recorded as a significant difference and vice versa.

3.3. Results

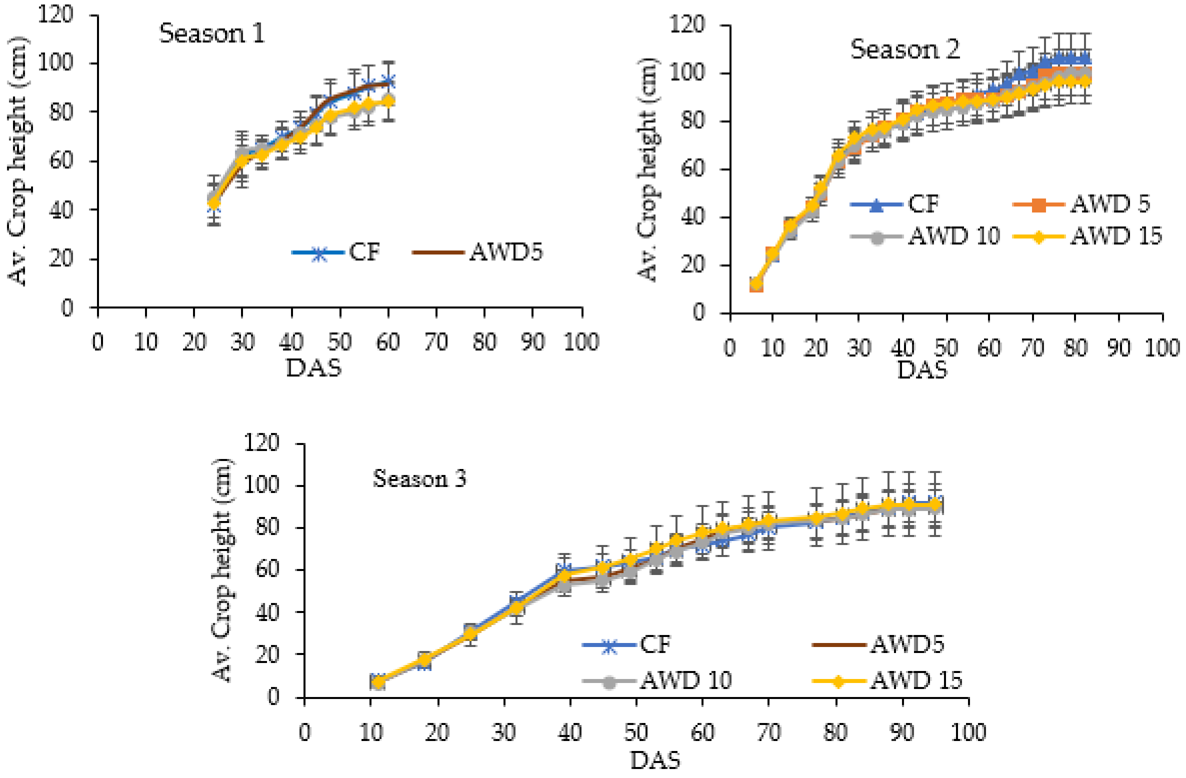


Figure 3. 7: Average crop: height, where Av.; Average, DAS is days after direct seeding, CF; continuous flooding irrigation, AWD; alternate wetting and drying irrigation practice.

3.3.1 Water Regimes on Rice Growth and Tillers

Figure 3.7. shows the average crop height with different water regimes during various cultivation seasons. There was gradual difference in rice growth among different water regimes. Forty days after direct seeding, CF and AWD15 had small differences in crop height on AWD10 and AWD5. The crop height difference is attributed to changes in water regimes. At heading the lowest crop height was noticed slightly in CF, AWD 5 and AW10 while comparable height increments were observed in AWD 15. In addition, crop heights at grain filling and maturing stage were nearly the same under all water regimes.

In addition, tillering is an important trait in grain production, though the productivity of rice plants is highly dependent on the number of effective tillers with panicles bearing at least one filled grain rather than the total number of tillers (Mboyerwa et al., 2020). Figure 3.8 shows the effect of different water regimes on crop tillers. Initially, the number of tillers was nearly the same under all the water regimes though between 40 to 50 DAS, AWD15 and CF had a higher number of tillers compared to AWD5 and AWD10 during winter period. Towards the end of the vegetative stage, to the grain filling, CF had a slightly higher number of tillers compared to all the AWD treatments. The water regimes did not significantly affect crop height and the number of tillers.

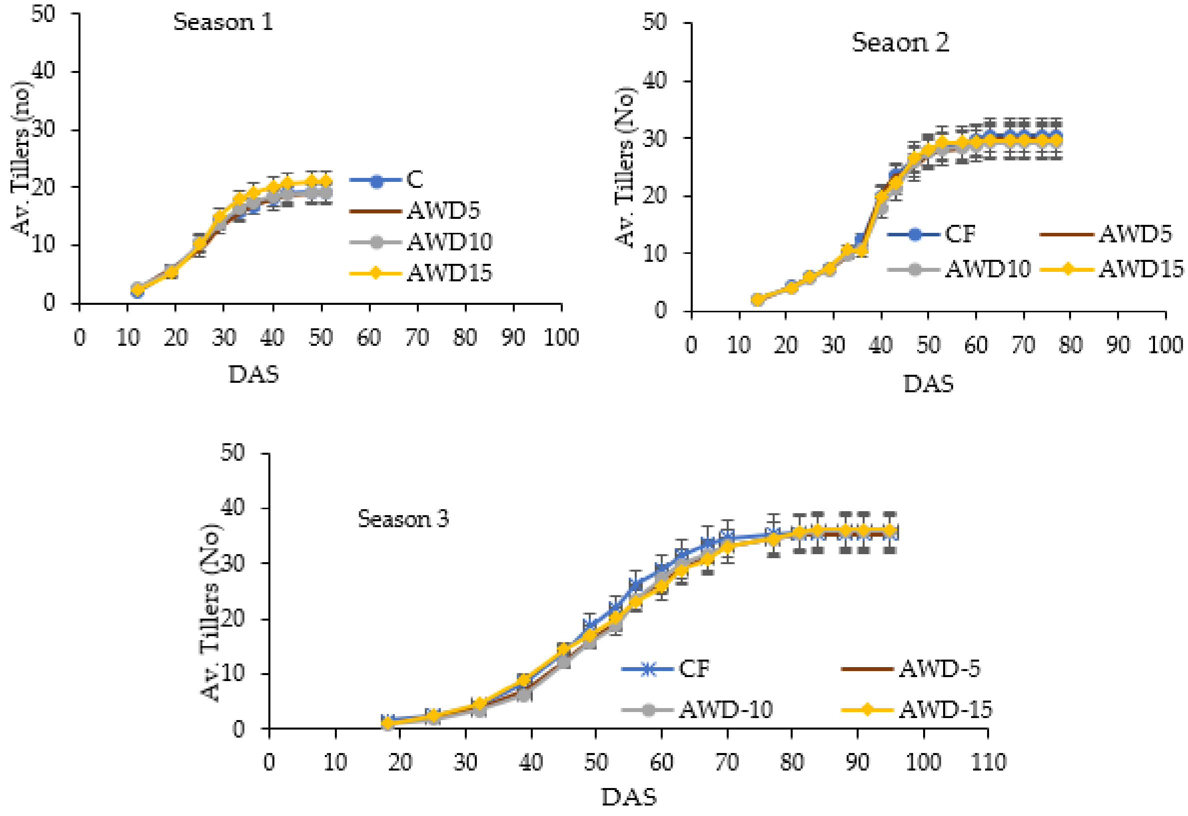


Figure 3. 8: Average crop tillers where Av.; Average, DAS is days after direct seeding, CF; continuous flooding irrigation, AWD; alternate wetting and drying irrigation practice.

3.3.2: Water regimes on yield and yield components

The results of crop yields, number of panicles, grain number and percentage of mature grains are shown in Figure 9 and 10. There was no significant difference for the yields observed in all water regimes, however, CF (0.172 kg) had a slight difference of 0.028, 0.034 and 0.012 kg in the yields compared with AWD5, AWD10 and AWD15 respectively. In addition, CF and AWD15 had the same average number of tillers with a slight difference of 6 and 8 number of tillers observed in AWD5 and AWD10.

On the other hand, grain maturity is an important factor in determining the optimum harvest time and affecting grain yields. Water regimes affected the number of grains and their maturity. The number of grains was highest in AWD5 with 7034 as compared to the other water regimes with 6601, 4371 and 5421, corresponding to CF, AWD10 and AWD15, respectively during winter more grains in summer period. The AWD5 and CF had a similar range of grains with a slight difference of 433 grains. In addition, the lowest number of 4371 and 7581 grains were observed in AWD10 and AWD15 during winter and summer respectively. The percentage of mature grains in AWD10 and AWD15 were same. The highest percentage (76) of mature grains was observed in CF compared to 73 in AWD5 and 70 corresponding to AWD10 and AWD15

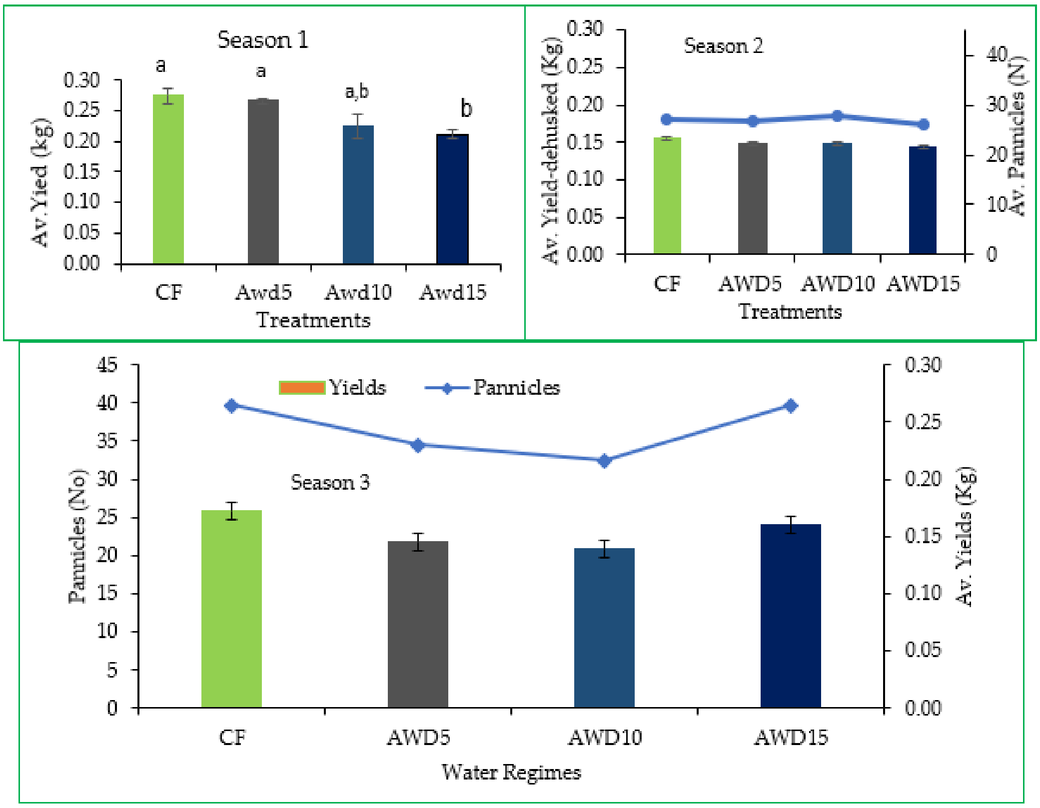


Figure 3. 9: Average crop yield and panicles where Av.; Average, DAS is days after direct seeding, CF; continuous flooding irrigation, AWD; alternate wetting and drying irrigation practice.

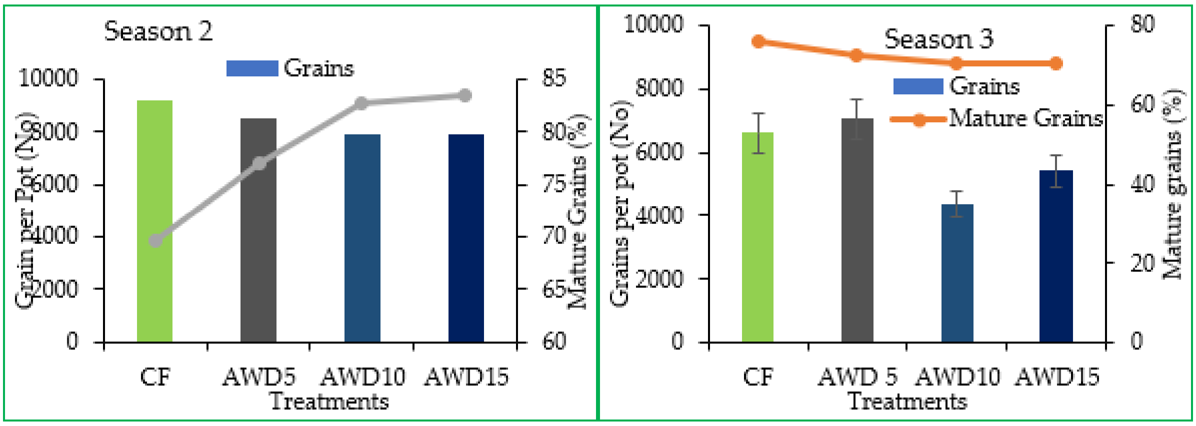


Figure 3. 10: Crop grain number and percentage of mature grains under AWD regimes where Av.; average, CF; continuous flood irrigation as control, AWD; alternate wetting and drying irrigation practice

3.3.3 HI and biomass dry matter with different water regimes

Figures 3.11 and 3.12 shows crop HI and percentage of dry matter content under different water regimes, respectively. The HI values in all AWD water regimes range from 0.685 to 0.480 kg/kg though CF had a slightly large HI value compared to AWD5, 10 and 15 respectively in all seasons. Similarly, the percentage of dry matter in AWD 5 and 10 were slightly higher than CF's. The highest percentage of nearly 33 % was observed in AWD 5 and 10 while the lowest percentage of dry matter content of 25 % was observed in AWD 15 during season 2.

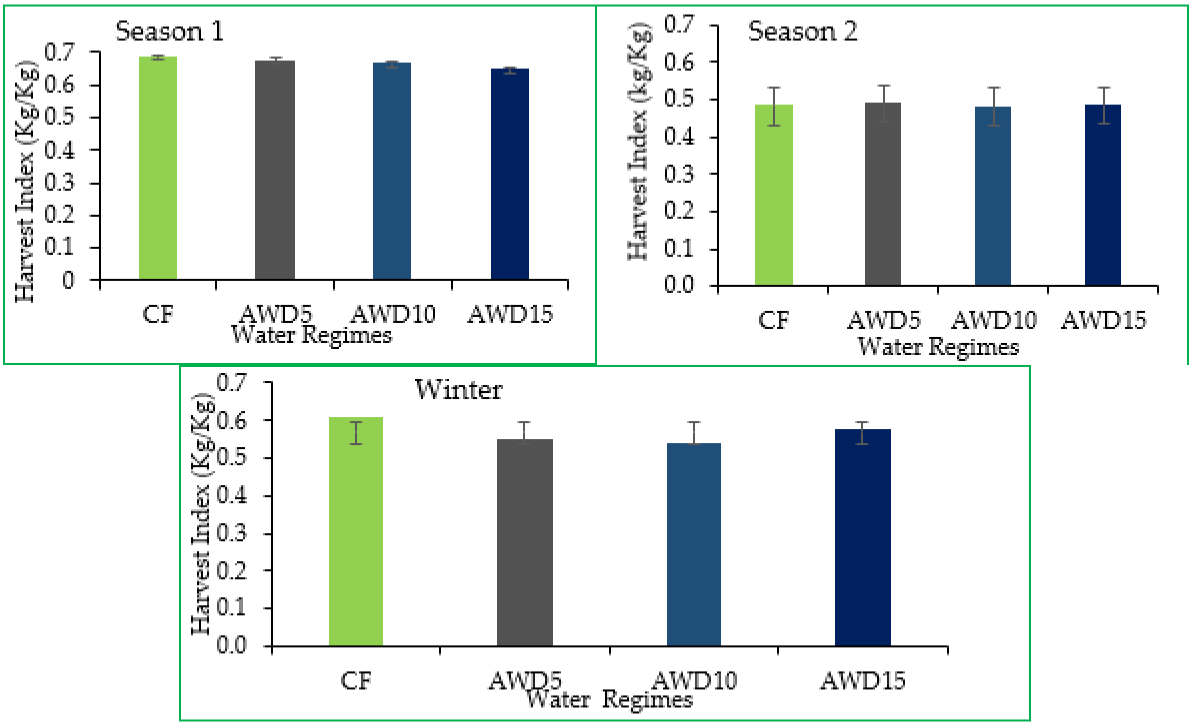


Figure 3. 11: Crop harvest indexes under different water regimes

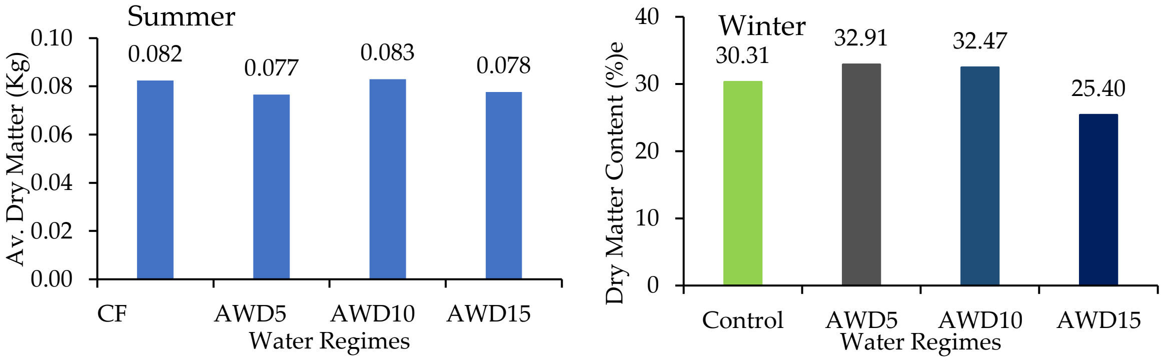


Figure 3. 12: Percentage of biomass dry matter content under different water regimes

3.3.4. Seasonal Water Use, Water Productivity and Water Saving

Table 3.2 summarizes the average seasonal pot water use and productivity with different water regimes during the three seasons. The seasonal water uses from direct planting to harvest represented 121, 78, 76 and 89 L under CF, AWD 5, 10 and 15, respectively during winter period, different from 89, 77, 57 for both 10 and 15 during spring, 117, 98, 102, and 96 during winter period. The highest season water use was observed in CF (121 L) and lowest under AWD 10 (76 L). On the other hand, seasonal water use demonstrates water saving in AWD 5, 10 and 15 conditions by 35, 37 and 26% respectively. Table 3.2 summarizes the water productivity and water savings in all three seasons. It was also observed that rice plants required more water during their mid to late vegetative growth stage; however, this depends largely upon local soil and climatic condition, as mentioned by Chapagain and Yamaji (2010).

Table 3. 2: Average seasonal pot water uses and productivity.

Season	Water Regimes	Water use (L)	Water Productivity (Kg/m^3)	Water Savings (%)
Season 1: Spring	CF	89	3.07	-
	AWD5	77	3.46	14
	AWD10	57	3.89	36
	AWD15	57	3.67	36
Season 2: Summer	CF	117	1.33	-
	AWD5	98	1.51	16
	AWD10	102	1.47	13
	AWD15	96	1.50	17
Season 3: Winter	CF	121	1.43	-
	AWD5	78	1.86	35
	AWD10	76	1.83	37
	AWD15	89	1.81	26

Note: CF; continuous flood irrigation as control, Av.; Average, AWD; alternate wetting and drying practice, Wp; water productivity. Water productivity in season 1 is based on fresh yield after harvest while those in season 2 and 3 is based on dry grain yield measurements after rice threshing.

3.3.5. Redox Potential Under different soil water regimes

The soil redox potential is one of the factors that affects greenhouse gas emissions in the paddy fields. Figure 3.13 shows the variation of soil redox potential with soil water regimes. After water application, the redox potential changed, and the values were found lower in AWD5, AWD10 and continuous flooding. During the booting to flowering stage marked from March 30th to March 19th, the soil has higher oxidation conditions in all AWD compared with CF on ranging from 207 mV to 590 mV. Although after the flowering stage, negative soil redox potential values were seen in AWD15 compared to even control. The AWD5 and AWD10 showed significantly higher redox values than CF and AWD15, more so towards the harvest. Generally, the redox potential was strongly related to the duration and depth of standing water.

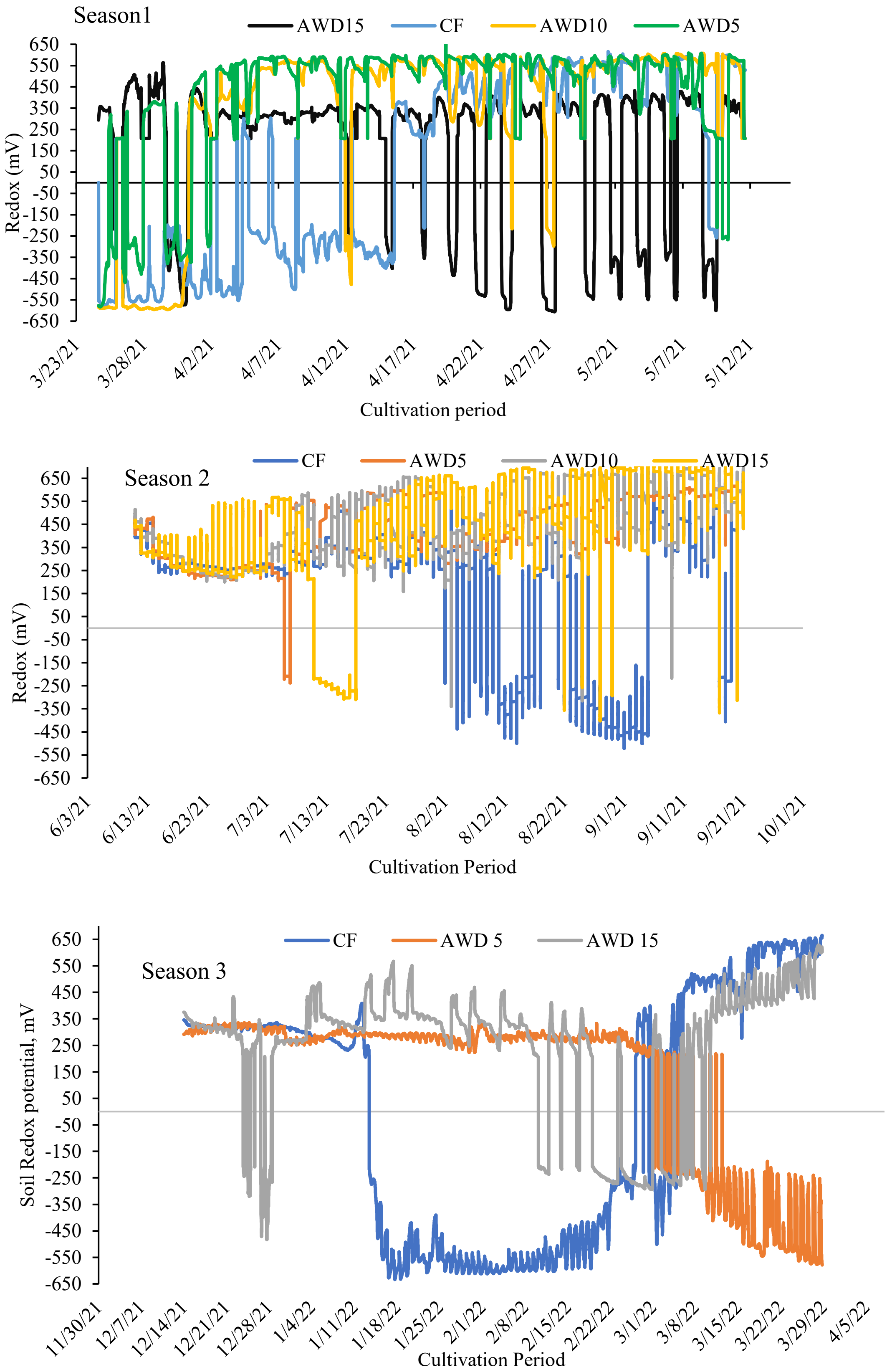


Figure 3. 13: Changes in soil redox potential under water regimes

3.3.6. LAI Under different Water Regimes

Figure 3.14 shows the variation of leaf area index (LAI) under different water regimes with rice cultivation. LAI for three selected water regimes thus CF-control, AWD5, and AWD15 to represent AWD irrigation conditions. Initially there was gradual increase in LAI and was nearly same during the first 30 DAS—days after direct seeding, although after 45 DAS, CF had higher LAI compared to the AWD water regimes. Generally, all water regimes had high LAI after 60 DAS and in comparison, with open field condition. The maximum LAI values in all water regimes varied from 17-23 which was 3 to 5 time higher compared to the LAI value of 5 of research by Li et al., (2019). The high LAI was attributed to differences in water regimes, fertilizer application and small surface area of the pots compared to the actual ground surface with field conditions.

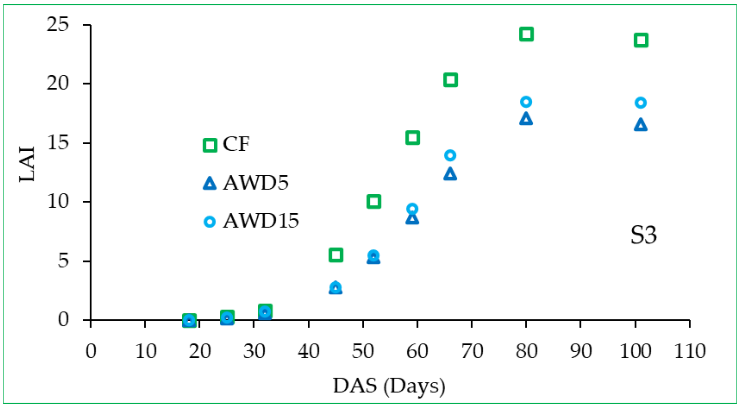


Figure 3. 14: Variation of leaf area index under different water regimes.

3.3.7. Variation of soil water pressure heads

Figure 3.15 shows the variation of soil water pressure heads under different water regimes. The observed pressure heads show negative pressure in all water regimes, even in CF. The variation in pressured head corresponds to the crop stage and is proportional to the water regimes (Fig. 3.14), indicating soil drying conditions during crop growth. The soil drying condition is high in AWD regimes compared to CF and it's related to the different water regimes, crop density and the crop growth stage —vegetative and maturity stages, due to root growth which influence the root water uptake.

Similarly, the low-pressure head is attributed to discrepancy between the actual water level, measured water level and irrigation frequency with the water regimes. This can be defined by the difference between when water dropped to the required pre-defined condition in the observation tubes for AWD regimes and zero ponding for CF, and time of water application. This was influenced by crop density and small size of the pots resulting in frequent soil drying and frequency cycles.

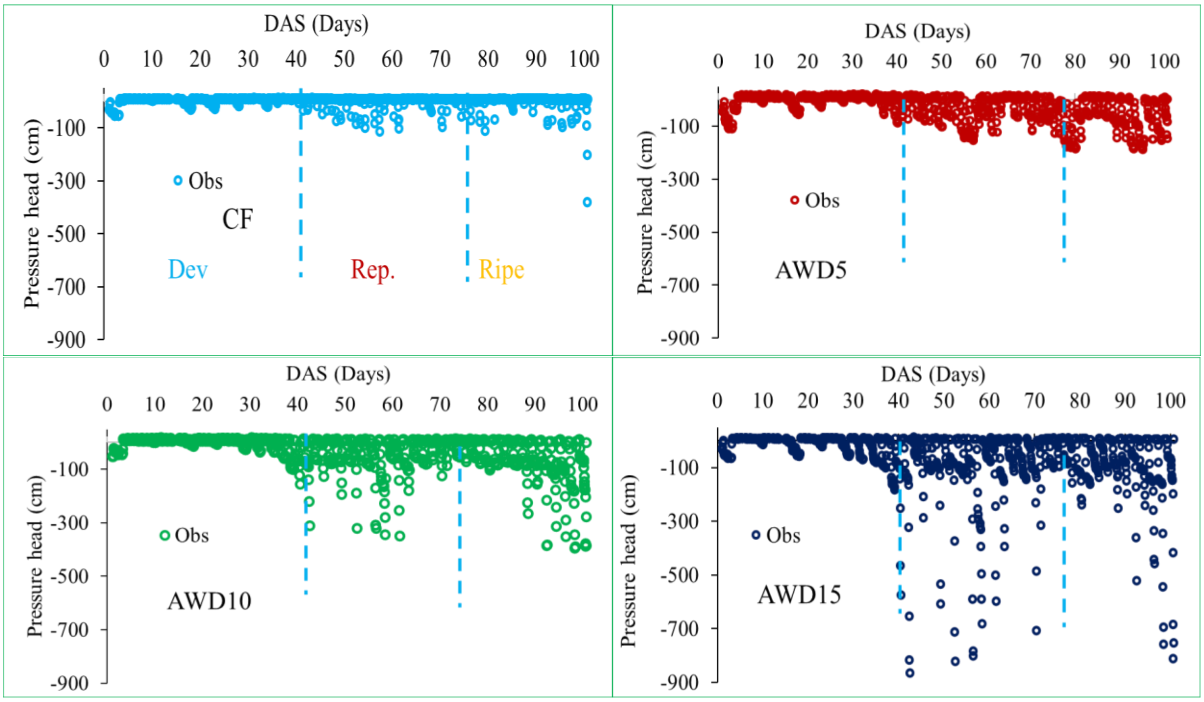


Figure 3. 15: Changes in soil water pressure under water regimes

3.4. Discussions

3.4.1. Effect of water irrigation regimes on rice growths & tillers

In AWD practice, paddy soils are subjected to periodic irrigation and drying conditions which are related factors such as irrigation, air temperature, soil type and properties [40]. In this research, the water regimes were applied 17 days after seeding (DAS), which is in line with IRRI recommendations. The water application in different water regimes varied according to the rice growth stages. Water ponding depth varied from 2-4 cm, while its duration under all water regimes at tillering to vegetative stage varied from 2 to 7 days, though this changed to 1 to 2 days under AWD conditions and even to half day in both CF and AWD conditions, at grain formation and maturity. Rice is sensitive to any severe water stress, and this was observed in plant height reduction at the end of booting to panicle initiation (AWD5 and AWD 10) and maturity stage (AWD10). Any change in water application tends to induce drought stress contributing to a decline in net photosynthesis and reduced growth through the inhibition of cell elongation or cell division (Pascual et al., 2017). Similarly, the induced short water stress in this research was observed with difference in crop height and tiller numbers in AWD conditions compared with CF between 49 to 70 DAS (Kima et al., 2014). Additionally, not all the tillers were developed to maturity (productive tillers). Some degenerate to become dormant when young and die later depending on environmental and nutritional conditions, affecting the final yields (Horie et al., 2005). The rate of the crop recovery due to re-water application depended on the soil conditions such as soil water, pre-drought intensity and duration of soil drying, which was very short of causing visible water stress in all AWD conditions during the studied period (Xu et al., 2010). On the contrary, and due to short soil drying periods in this study, crop growth and tillering were insignificantly affected by water regimes. This is in support of the research by Nguyen et al., (2009), who compared various water-saving systems in rice and found an insignificant difference in tiller number among water regimes. The same study also suggested that tillering was less sensitive than other characteristics, such as plant height and leaf area.

3.4.2. Effects of water irrigation regimes on yield and yield components

The results demonstrate that yields, numbers of panicles and grains, and percentage of mature grains were not significantly affected by the water regimes. However, there were slight declines in yields, grains and percentage of mature grains. Much as the induced invisible short water stress seem to have occurred due to water applications with different water regimes. This was not critical, since the amount of water application based on different regimes contributed to the infiltration rate that coincided in time with water uptake (Pascual et al., 2017). The availability of soil water conditions did not reach a critical point for crop to develop deeper root system as an adaptation measure but also due to the depth of the pots. The decline in the percentage of mature grains is supported by Kumar et al., (2006) who indicated that the percentage of unfilled grains was significantly higher in sites that were affected by drought at the reproductive stage. Further research by Davantgar et al., (2009) showed that any water stress at flowering causes flower abortion and an increase in unfilled grain percentage. This induces spikelet sterility or grain filling delay leading to high unfilled grain percentage which further reduce overall grain yield as observed in AWD 10 and AWD 15. Additionally, the delay in plant growth, due to any induced water stress during panicle initiation delays the heading rate decreasing panicle number and grain formation (Chapagain, and Yamaji, 2010). Since any water stress at panicle initiation is more destructive to panicle number biomass dry mass, and total grains, irrespective of the cultivars resulting in drastic decrease per hectare in paddy yield as noted by Akram et al. (2013). However, in this research, the number of panicles for each water regime produced similar results though decreased average yields with the AWD conditions.

3.4.3. Harvest Indexes and biomass dry matter content with different treatments.

The water regimes had insignificant effect on HI of the rice as observed by HI values of 0.607, 0.550, 0.538 and 0.576 Kg/Kg corresponding to CF, AWD 5, AWD 10 and AWD 15, respectively. This could have been due to the similarity in morphological aspects of vegetative growth such as same time of head initiation, duration of grain heading, biomass accumulation in formation of stems, leaves at heading and decline in grain filling affecting the final yields in the same rice cultivars as noted by Elkheir et al., (2013), which is the similar case in this research. The study by Chen et al., (2001) on the rice cultivars also showed the similarity in the change of stem biomass between aerobic rice cultivars and little increase after the booting stage, whereas differences in duration from the booting stage to the heading stage. Other research indicates that seed priming reported its effect on harvest index and reproductive stage components. Its attributes may be to pre-germination metabolic activities that make the seed ready for radical protrusion leading to good crops establishment (Elkheir et al., 2018; Arif et al., 2010). Similarly, our results indicated that biomass dry matter content was not affected significantly. However, the highest percentage of biomass dry matter was produced under AWD5 (33%), followed by AWD 10 (32%). Further, the lowest biomass dry matter content was observed in AWD 15 (25%). Therefore, the application of fertilizer at the appropriate rate and time with different water regimes can improve above-ground biomass and can increase rice yield as observed by Haung et al., (2016) since the effects of water and nutrients on crop growth, yield and HI are interactive (Sicheng et al., 2022). Our findings also demonstrated the potential to increase the HI of rice with direct seeding.

3.4.4: Seasonal water use, water productivity and water saving.

Generally high irrigation WP was produced in all AWD conditions, with the highest WP (1.86 kg/m3) observed in AWD 5, followed by AWD 10 and AWD 15 with 1.83 and 1.81 Kg/m3 respectively, compared to CF (1.43 Kg/m3). However, the lowest yield reduction (0.033 kg) and highest immature grains (30 %) was observed in AWD10, indicating that 0.033 kg of yield was lost for saving 1 m3 of water compared with CF. Similarly, research on different water regimes by Zhang et al., (2010) observed a significant increase in grain yield and water use efficiency when soil water potential was reduced to 25 kPa in AWD. This indicates that drying period with AWD water regimes is the major factor affecting paddy yield, though soil drying to 25 kPa is beneficial to grain growth during grain filling. Based on the AWD conditions, the soil drying varied from 2-5 days at the crop development stage and 0.5-2 days at the reproductive and ripening stages. On the other hand, an increase in water use in all water regimes was observed towards end of the vegetative stage to ripening as seen in Figure 8. Also, AWD15 had high seasonal water use as compared to other AWD regimes due to increased water use in different pots with the same treatment due to changes in plant morphological activities in vegetative and ripening stages. It was observed that irrigation water application in paddy with AWD conditions must be carried out as soon as water drops the required soil depth to avoid any induced water stress, which may affect rice productivity. AWD15 was accepted as the best irrigation practice among the other different irrigation management with a 26.3 % reduction in water use and only a 6.7 % reduction in grain yield compared to the CF, AWD 5, and AWD 10 conditions.

3.5. Summary

The objectives of this chapter were research to (1) to apply and evaluate FWL of safe AWD practice and 2) examine the effect of AWD regimes on water productivity, water saving, and harvest indexes:

- The grain yield of paddy rice did not reduce significantly in AWD conditions. The reduction is ineffective so long as the soil moisture is in the range of readily available water for the rice depending on the soil type and soil hydraulic conditions.
- Any induced water stress due to different water regimes especially at panicle and grain formation, can delay rice growth, cause a difference in number of tillers panicles and yields.
- AWD has potential of improving irrigation water productivity with insignificant difference in yields and increase the HI of paddy rice. Timely water application, fertilizers can contribute to yields, biomass and HI.
- AWD15 was accepted as the best irrigation practice due to a 26.34 % reduction in water use and only a 6.40 % reduction in grain yield compared to the control continuous flooding treatment.
- Estimated LAI was high under all water regimes.
- Soil water pressure was proportional to water regimes with negative soil water pressure head in CF with up to -900 cm in AWD 15 regime.

The findings of the present study provide data reference from glass greenhouse conditions for theoretical scientific knowledge and understanding of safe AWD practice. This is a support for water management and water saving in paddy rice cultivation with safe AWD practice applied throughout the whole cultivation period, in countries facing water shortages. Given that our study was conducted in glass greenhouse conditions, it is important to conduct this research in in-situ field conditions. Water application by both matric potential and FWL with safe AWD practice throughout the whole cultivation period on different paddy soil types should be evaluated. Effects on water, crop productivity and clay physical properties such as hydraulic conductivity, expansively and plasticity should be further explored.

Chap. 4: Quantitative Evaluation of Water Flow in Paddy Soils

4.1. Background

Water flow in rice paddy fields involves the interaction of very complex processes, and their measurements and evaluation under field conditions is usually difficult, costly, and time-consuming. Several scientists have increasingly used computer models to study such complex processes in the soil and provide water management and planning guidance. HYDRUS-1D and HYDRUS (2D/3D) are numerical models used by several researchers to simulate waterflow in agricultural fields with different crops and various irrigation schemes (Šimůnek et al., 2012). However, the HYDRUS-1D model has not yet been used for studying water flow in pots with directly seeded rice paddy conditions. Further, in AWD water regimes in the pot experiment, the plants benefit from the frequent multiple water applications for plant growth (Lu et al., 2018. This water management produces distinctly different characteristics of the water flow regime and water losses from rice paddy pot experiments compared to the rice paddy field conditions.

The objectives of this chapter were to evaluate water flow in paddy rice under AWD regimes using the HYDRUS-1D model using field experimental data to understand soil water balance conditions in paddy rice fields. The water applications, water balance, and crop water productivities of the paddy rice differ during the paddy cultivation and data for two seasons (Feb-May/20221 and June-Sept/20221) have been used in the simulations. Therefore, the soil regimes, soil potential and water balances are compared with Continuous Flooding (CF) as control with direct seeding in all treatments in the two consecutive seasons.

4.2. Materials and Methods

The study was carried out from February 2021 to March 2022 in the closed system—Phytotron at Tokyo University of Agriculture and Technology (TUAT), Fuchu described by the Longitude and Latitude of 139.4787° E, 35.6840° N, respectively and 67 m above sea level. The details on site description, rice cultivation is described in chapter 3. In this chapter, experimental data for two seasons (season 1 and season 2) with paddy rice cultivation was used in HYDRUS-1D modelling.

4.2.1 Simulation Procedures and HYDRUS-1D Model Description

The HYDRUS-1D is a one-dimensional model that simulates vertical water movement, solute transport, and water uptake crop (Simunek *et al.*, 2008). The program numerically solves Richard's equation for water flow in saturated and unsaturated zones (Simunek et al., 2012). The governing one-dimensional water flow equation for a partially saturated porous medium can be described based on the modified form of the Richards equation, with the assumptions that the air phase plays an insignificant role in the liquid flow process and that waterflow due to thermal gradients can be neglected (Yong et al., 2013):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S \tag{4.1}$$

Where h is the water pressure head (cm), θ is the volumetric water content (cm^3/cm^3), t is time (d), z is the spatial coordinate (cm), $K(h)$ is the unsaturated hydraulic conductivity function (cm/day), and S is the sink term in the flow equation ($cm^3/cm^3/day$) accounting for root water uptake.

The soil water retention, $\theta(h)$, and hydraulic conductivity, $K(h)$, functions according to van Genuchten (1980), are given as

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} \tag{4.2}$$

$$\theta(h) = \theta_s \quad h \geq 0 \tag{4.3}$$

$$K(h) = K_{sat} S_e^l [1 - (1 - s_e^{1/m})^m]^2 \tag{4.4}$$

Where experiments θ_s is the saturated water content (cm^3/cm^3); θ_r is the residual water content (cm^3/cm^3); m, and n are empirical shape factors in the water retention function, where m = 1 − 1/n; K_{sat} is the saturated hydraulic conductivity (cm/day) measured using soil column experiments; l is the shape factor in the hydraulic conductivity function; and S_e is the effective saturation (-), which is defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4.5}$$

Since the profile is small and water flow in the soil profile is from the soil surface to the bottom of the pots the flow is predominantly in the vertical direction.

4.2.2 Initial and Boundary Conditions

The initial condition was defined using the measured pressure head distribution. The upper boundary surface conditions: irrigation, evaporation, and transpiration, were subjected to the atmospheric boundary conditions with a surface layer (maximum of 5 cm) in all the rice growth stages. In this study, the potential evaporation, E_p, potential transpiration, T_p, and irrigation fluxes were used to represent the atmospheric boundary conditions. Using the observed pressure head data, we considered the bottom boundary of the pots with zero flux since the pots were closed. The soil profile pressure head was defined according to the pot size with upper and lower bounds of 5 and 30 cm (Figure 4.1) and the crop roots were restricted to the size of the soil column.

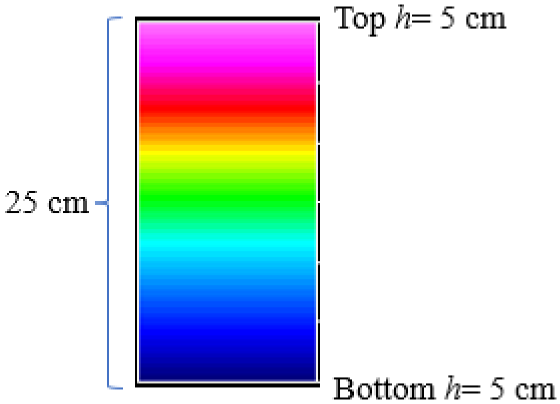


Figure 4. 1: Illustration of soil profiles defined by the pressure head in HYDRUS-1D.

4.2.3 Root Water Uptake Functions

Root uptake as volume of water taken by plant per unit volume of soil per time was determined by Feddes formula (Feddes et al., 1978).

$$S(h) = \alpha(h) \times S_p \tag{4.6}$$

Where S_p is the potential water uptake ($cm^3/cm^3/d$) and $\alpha(h)$ is the reduction term of the root water uptake function generally taking from 0 to 1. The method to consider water stress was used to determine root water uptake. The Feddes model parameter values optimized by Singh et al. (2003) for rice crops (h_1= 100 cm, h_2= 55 cm, h_3 (high) = −160 cm, h_3 (low) = −250 cm, and h_4=−15,000 cm) were used to parameterize the water stress response function proposed by Feddes et al. (1978) and Homaee et al. (2002). Parameters h_1 through h_4 represent different pressure head values, which affect root water uptake in the soil (Figure 4.2). The water uptake is assumed to be zero for $h > h_1$. For $h < h_4$ (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure heads between h_3 and h_4 (or $h_1$and h_2), water uptake linearly decreases (or increases) with h.

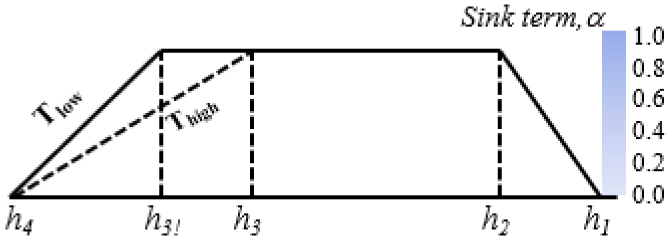


Figure 4. 2: Schematic illustration of crop water uptake function, alpha proposed by Feddes et al., 1978.

4.2.4 System Characteristics & Potential Evapotranspiration, ET

HYDUS-1D requires potential evaporation (the upper boundary condition) and potential transpiration (a sink term in the Richards equation) fluxes to be specified as separate input values at a daily time step, to simulate the influence of soil water on transpiration (root water uptake). The reference evapotranspiration, ETo, and the crop coefficient, K_C, were used to determine the potential crop evapotranspiration ET_C under normal conditions as (Allen et al., 1998.

The Penman-Monteith equation was used to estimate reference evapotranspiration (ETo) from the observed meteorological data—Air Temperature; Relative Humidity; Wind Speed and Solar Radiation. The ETo, and crop coefficient, Kc was used to determine the potential crop evapotranspiration ETc under normal conditions.

$$ET_o = \left(\frac{0.408\Delta[(R_n - G] + \gamma \frac{900}{T+273} u_2 \, (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \right) \tag{4.7}$$

Where:

ET_o = reference crop evapotranspiration (mm/day), R_n = net radiation at the crop surface [MJ m-2 day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = air temperature at 2 m height [°C], U_2 = wind speed at 2 m height [m s^{-1}], e_s = saturation vapor pressure [kPa], e_a = actual vapor pressure [kPa], e_s- e_a= saturation vapor pressure deficit [kPa], Δ = slope of vapor pressure curve [kPa °C^{-1}], γ = psychometric constant [kPa °C^{-1}].

$$ET_c = ET_o \times K_c \tag{4.7}$$

Since rice crop partly covered the ground surface, partitioning ET_c into E_p and T_p was necessary (Figure. 4.3). This was achieved using leaf area index (LA) given by the equations (Belmans et al., 1983), a function of the crop development stage:

$$E_p = ET_c \times e^{-k_{gr} \times LAI} \tag{4.8}$$

$$T_p = ET_p - E_p \tag{4.9}$$

where K_{gr} is the extension coefficient for global solar radiation (taken as 0.3 for the rice crop: Li et al. 2014) and LAI is the leaf area index. The values of the LAI used in HYDRUS-1D were measured manually (chapter 3 above) since the experimental conditions were the same in all the seasons.

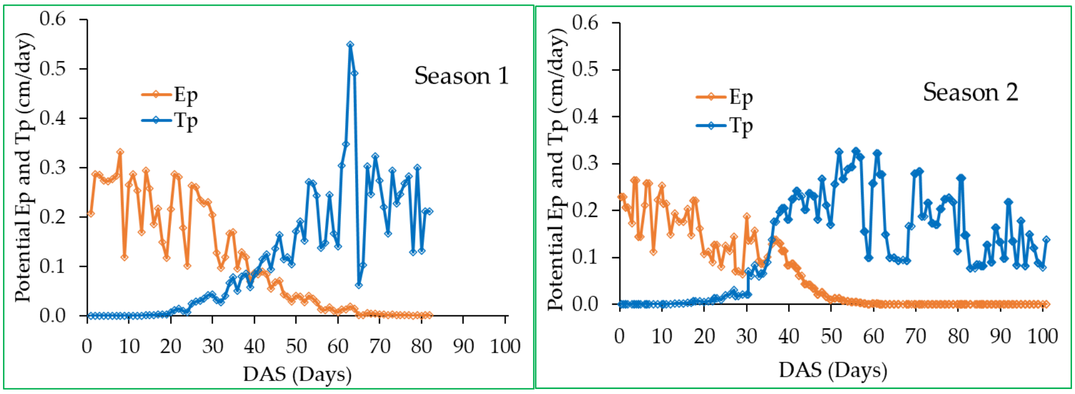


Figure 4. 3: Potential evaporation, Ep, and transpiration Tp

Rice cultivation in pots and in closed system—phytotron (Chapter 3) is unique and different compared to lysimeter and the field conditions since evapotranspiration (ET) plays a key role in irrigation application. The air circulation enhances ET, although the average wind speed is relatively small as evidenced by the air speed measurements (0.49 and 0.33) inside the phytotron (Figure 4.4). The air circulation is located at the top of the phytotron while the ATMOS41 weather station is installed at 1m above the ground surface (Figure 4.5).

Additionally, the 1/5000-a Wagner pots (4.0 L, 24 cm in diameter, 30 cm in height) influenced the size and depth (25 cm) of soil column with three crops directly seeded per pot. Therefore, the crop roots are restricted to the pot size thus small pot sizes, and soil column for irrigation water and fertilizer, since crops absorb nutrients and water from small volumes of pots while water and nutrient loss frequently leads to frequent water application (Lu et al., 2018).

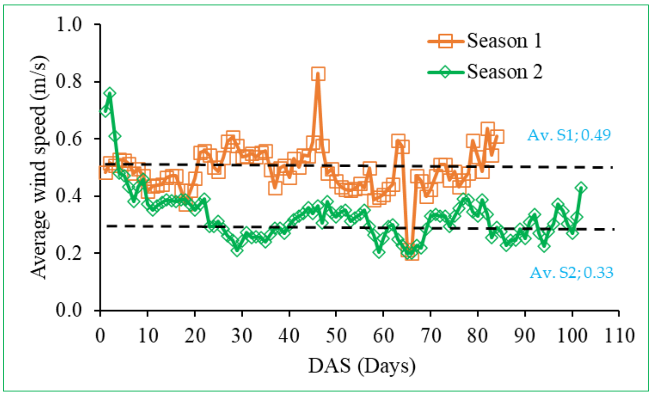


Figure 4. 4: Variation of wind speed in greenhouse during paddy rice cultivation.

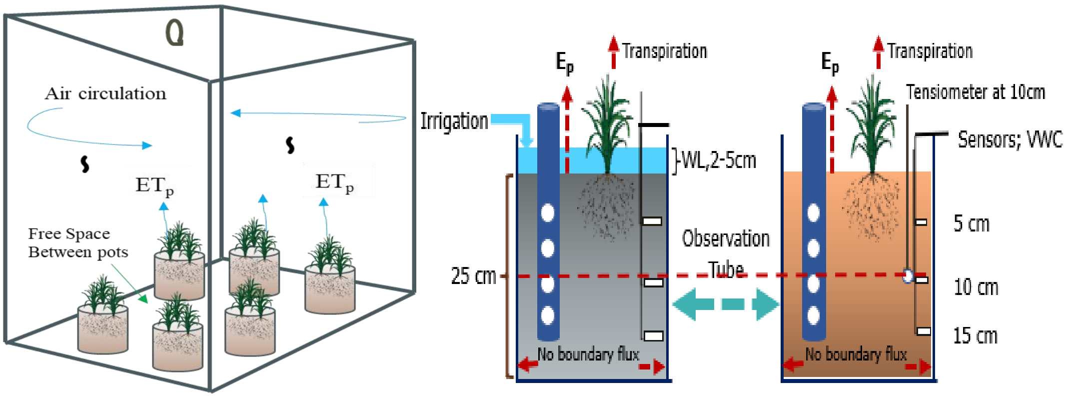


Figure 4. 5: Illustration of closed system —phytotron (a) and water balance components of paddy rice cultivation (b), at pot scale.

4.2.5 Adjusting Potential ET

The ET process of the pot crops (Figure 4.5) differs from the field and lysimeter since the crop is limited to the size of pot, soil column in the pot and crop density. The crop roots absorb water and nutrients from the smaller volume of soil column in pot and the representative pot area differs from open field conditions (Lu et al. 2018). This has significant implications on the root water uptake after crop emergence there by water, and nutrient stress would occur more frequently there by increasing water application. Modification of ETo for pots and containers cultivations should be considered for improving the ET in pot conditions. This study has developed equations to correct ETo for the pot-based experiment.

$$C_f = \frac{SA_G}{SA_{pot} \times P_n \times N_p} \tag{4.8}$$

The pot evapotranspiration (ET_{pot}) as adjusted potential ET was estimated from the relationship between the ETo based on the standard PM-FAO and the correction factor, using the equation below.

$$ET_{Pot} = ET_o \times C_f \tag{4.9}$$

Where: SA_G, SA_{pot}, Pn and Np denote the phytotron's surface area, the pot's surface area, the number of pots/containers, and the crop density/no of plants per pot, respectively. C_f is the correction factor, and ET_{pot} is the modified ET for pots.

4.3 Soil Physical Properties and Hydraulic Parameters

The van Genuchten hydraulic parameters, θ_r, θ_s, m, α and n (Table 4.1), which are required by the HYDRUS-1D model, were estimated from the simple evaporation method (Peters et al., 2015) using by fitting retention data, $\theta(h)$, measured using the Hyprop software. The pore connectivity parameter (l) was assumed to equal an average value (0.5) for many soils (Li et al., 2014).

4.3.1. Lab Analysis: Dry Density, Bulky Density and Porosity

Understanding paddy fields' soil physical and hydraulic properties is vital in improving irrigation water management. Soil samples were collected from the Tokyo University of Agriculture and Technology paddy research field from 0-60 cm soil layer. The samples from 0-30 cm soil layer were mixed to form homogenous soil used for the pot experiment. The soil was taken in the environmental soil physics and hydrology laboratory of Tokyo University of Agriculture and Technology (TUAT) for analysis. The soil's physical and hydraulic properties included bulk density, dry density, particle density, porosity, soil penetration strength, and soil texture, while the chemical properties measured included total carbon (TC) and total nitrogen (TN).

Soil dry density refers to the ratio of the total dry mass of soil to the total volume of soil. The dry density was important while packing the homogeneous soils in the pot experiments to attain the same field conditions as described in Chapter 3. Soil porosity enhances the space for microbial growth and activity in the paddy soils, thereby improving aeration, nutrient availability, water drainage and soil water retention capacity. Nine core samplers of 100 cm^3 were taken in the field with three sample representatives of each layer from 0-10, 10-20 and 20-30 cm and their labels noted and recorded. The weight of each empty core sampler was recorded (W_a). The soil sample from the undisturbed soil was collected from the research site and their weight was measured and recorded (W_b). Then the soil samples were put in the oven to dry for 24hours at a temperature of 1050c at the environmental soil physics and hydrology laboratory, TUAT. The weight of dried samples was measured and recorded (Wc). The bulk density (P_b), loss in soil moisture content (M_w), soil dry density (P_d), of the soil samples were calculated from the equation below.

$$\mathrm{P_b} = \frac{\mathrm{W_b} - \mathrm{W_a}}{\mathrm{V}}, \qquad \mathrm{M_w} = (\mathrm{W_b} - \mathrm{W_c}), \qquad \mathrm{P_d} = \frac{\mathrm{M_s}}{\mathrm{V}}, \ \text{Porosity} = (1) - (\frac{P_b}{P_d}) \tag{4.10}$$

Where: Ms; the Mass of the core with soil after drying minus the mass of core.

V; the volume of core sampler ($100cm^3$)

Figure 4. 6: Soil sampler cores and measurement of soil dry density of paddy soil samples in the Environmental Soil Physics and Hydrology Lab, TUAT, Japan.

4.3.2. Lab Procedures for Particle Density Analysis

Three sets of pycnometer flasks with glass stoppers were selected and their numbers were noted. Also, their masses were measured and recorded. Fill the air-dried soil sieved with 2mm sieve into the pycnometer flask up to a third of the flask followed with water slowly up to ¾ of the volume of the flask while mixing soil and water thoroughly by vigorously shaking the flask. The air bubbles were allowed to rise to the surface and measured and recorded the mass of the pycnometer and the mixture. Place the pycnometers containing the mixture of soil and water on the fine sand of the hot plate set at varying temperatures of 160-230ºC. Observe the mixture for 40 minutes after the start of boiling to remove air and shake carefully during the process to avoid pouring off. Clean the flask by wiping off the soil. The pycnometer containing the soil water mixture was cooled in the water bath for a few 10 minutes, then add de-aired water to full, inserted the stopper. The mass of the pycnometer and mixture was measured& recorded followed by the temperature of the mixture after removing air by hot plate or desiccator. Selected and recorded the no and mass of three empty bowl/plate/evaporating dish and poured the whole mixture into bowl/plate. The samples were taken for oven drying at a temperature of 105^0c for 24 hours and the mass of the oven dried samples were measured and recorded. Finally, the soil particle density was calculated and recorded.

Figure 4. 7: Determination of soil particle density of the paddy soil at Lab soil physics, TUAT, Japan.

4.3.3. Soil Hydraulic Parameter Estimation: Simple Evaporation Method

The soil hydraulic properties, such as hydraulic conductivity and retention characteristics, indicate the relation between soil potential and soil moisture content. A broad range of methods exists for determining soil hydraulic properties in the field or laboratory (Arya, 2002; Dane and Hopmans, 2002). Direct measurements of soil hydraulic properties and retention characteristics are laborious, time-consuming, and often expensive. The numerical inversion of transient experiments is one of the most accurate ways to determine soil hydraulic properties, where the simplified evaporation method is one of the most popular methods (Simunek et al., 1998). The evaporation method simultaneously determines the water retention characteristic and the unsaturated hydraulic conductivity of the same soil sample, which is, therefore, reliable.

A comprehensive error analysis based on the simplified evaporation method indicated that it is a fast, accurate, and reliable approach in the estimation of soil hydraulic properties in the measured pressure head range (Peters and Durner (2008)). The evaporation method was modified to extend the measurement range to higher pressures significantly and the detailed description of this approach was described by Schindler et al. (2010a, 2010b).

4.3.4 Lab Procedures for Simple Evaporation Method

Sampled disturbed dry soils from the 2mm sieve were compacted in the core of 250ml/249cm^3 capacity, using the dry densities of 0.843, 1.02 and 1.12 g/cm^3 corresponding to the three soil layers: 0-10 10-20 and 20-30 depth, to achieve the field conditions. Place the soil core in de-aired water to saturate for a period of 24hrs.

Generally preparing the measuring device, consisting of sensor unit, and set up the sample in the measuring device to start and record the measurement automatically within the set time intervals. The detail of the procedure for the evaporation method is described in the HYPROP operation manual (UMS, 2015).

Figure 4. 8: Soil sampling and setting up simplified evaporation experiment at the soil physics Lab, TUAT Japan.

4.3.4 Estimation and Fitting Parameters Using HYPROP Software

HYPROP–Data Evaluation Software (HYPROP-DES) is a software window-based tool environment for evaluation of data measured using the Simplified Evaporation Method (Thomas et al., 2011). The software reads the recorded data in TensioView projects by the data acquisition software "TensioView™ and stored in <. tvp> files. The files are converted to HYPROP-DES files with the extension <. bhd> (single measurement campaigns) or <.bhdi> (multiple measurement campaigns). The summary of the operations of the HYPROP-DES is outlined below, and the details is described in the HYPROP manual (Thomas et al. 2011):

i. Specify all required parameters for evaluating the recorded experimental data, including project information, positions of tensiometers, etc.
ii. Raw data visualization, such as tensions and weight changes
iii. Estimation and data visualization for the soil retention and conductivity characteristics.
iv. Fit the hydraulic functions to the data and set the confidence limits of the optimized hydraulic parameters.
v. Exportation of graphs, raw and estimated data, fitted functions, and other parameters.

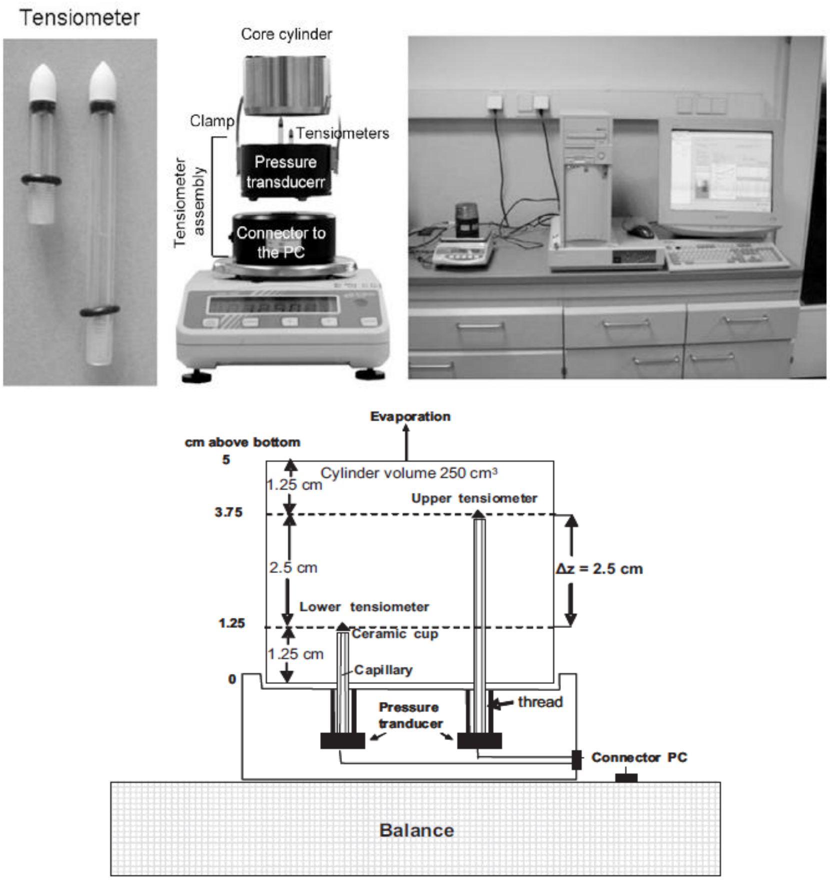


Figure 4. 9: Illustration of simple evaporation method. Source: Schindler et al., 2010.

Data and parameter fitting of functions using the HYPROP-DES is based on numerical procedures of HYPROP fit that fits the unimodal and bimodal nonlinear fitting. The software uses various hydraulic models, which include Brooks and Corey (BC), Fredlung-Xing (FX), Kosugi (K) and Van Genuchten, 1980). The equations below represent the three major models: Van-Genuchaten-1980 and Kosugi.

$$S_e(h) = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \frac{1}{[1+(\alpha|h|)^n]^m} \qquad (4.11)$$

$$\mathrm{K}(S_e) = K_s {S_e}^L \left[1-\left(1-{S_e}^{1/m}\right)^m\right]^2 \qquad (4.12)$$

$$S_e(h) = \frac{1}{2} erfc\left[\frac{\text{in}\left(\frac{\text{h}}{\text{h}_\text{m}}\right)}{\sqrt{2}\sigma}\right] \qquad (4.13)$$

Where, Se: Effective saturation [-], θ_s and θ_r: Saturated and residual water contents respectively [cm^3/cm^3], Ks: Saturated hydraulic Conductivity [cm/d], α [1/cm] and n [-] are semi-empirical parameters, m=1-1/n, and L is pore space connectivity parameter [-] can be fixed in HYDRUS-1D simulations following original study by Mualem (1976). h_m correspond to median pore radius, σ [-] is the standard function of log-transformed pored distribution density function.

Erf: error function

4.6. Results and Discussion

4.6.1: Soil Physical and Hydraulic Properties

Tables 4.1 and 4.2 the average values and variations for soil bulk density (ρ_b), particle density (ρ_p) texture properties, total carbon (TC) and total nitrogen (TN) and parameters of the water retention curves, as well as saturated hydraulic conductivities (Ks) measured from different soil layers of soils collected from the experimental paddy plots by laboratory analysis of core samples. The physical analysis indicates that the ρb increased as move down soil depth with highest value of 1.689 and lowest 1.447 g/cm^3 between 20-30 cm depth and 0-10 cm depth respectively. The bulky density and dry density vary slightly and low densities in the layer close to the soil surface with 1.447 and 0,843 g/cm3 respectively. Figure 4.10 shows the penetration strength of the paddy soils for the experimental field. The soils in the first layer between 0-10 cm has low penetration strength of 15.33 g/mm although the upper soils between 10-20 and 20-30 cm of the layer is hard with penetration strength of 22.83 and 23.17 g/mm, respectively. This is an indication for hardpan due to paddy field puddling which reduces the infiltration by closing the soil pore spaces.

Table 4. 1: Soil physical and chemical properties

Soil depth (cm)	ρ_b (g/cm^3)	ρ_p(g/cm^3)	Porosity	ρ_d (g/cm^3)	TC (%)	TN (%)	Texture Class
0-10	1.447	2.430	0.404	0.843	4.533	0.456	CL
10-20	1.618	2.130	0.240	1.019	3.538	0.346	
20-30	1.689	2.240	0.246	1.122	2.542	0.257	

Additionally the variation of soil water content (Wc) with pF values of the soil samples from the paddy research site, TUAT, Japan is shown in the Figure 4.11. Generally the method yielded very good estimates for water retention characteristics with pF range from 0-7. The water retention of the clay loam soil layers of 0-10, 10-20, and 20-30 cm varies from 52.6-68.7 % and 2.0-11.5 % at pF values of 1.8, and 4.2 corresponding to moisture content at saturation, and wilting point. The summary of the soil hydraulic parameters including the residue water content (θ_r), saturated water content (θ_s) is shown in Table 4.2. These results can be applied in improving irrigation schedule of the paddy rice.

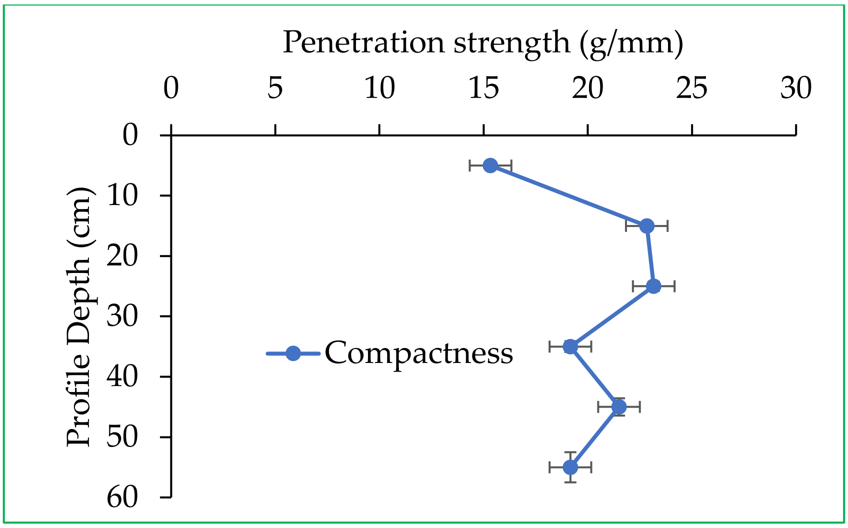


Figure 4. 10: Penetration strength of the paddy soils.

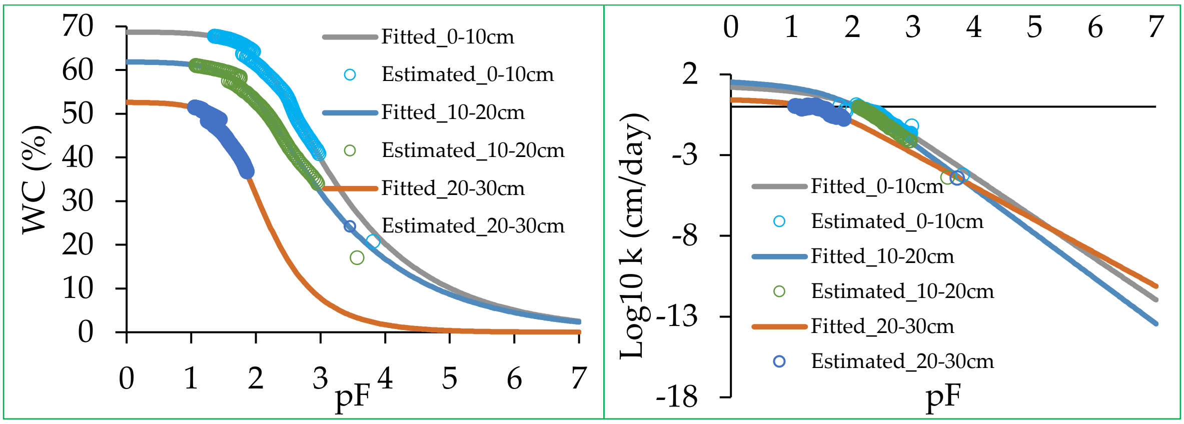


Figure 4. 11: Variation of soil water content with pF of paddy soils

Table 4. 2: The initial soil hydraulic parameters for different soil layers

Soil Profile	Θ_r (cm^3/cm^3)	Θ_s (cm^3/cm3)	α (cm^{-1})	n	K_s (cm/day)	l
0-10 cm	0.085	0.687	0.0057	1.302	25.8	-0.192
10-20 cm	0.115	0.619	0.0096	1.286	62.4	0.787
20-30 cm	0.020	0.526	0.0180	1.659	3.08	-1.914

Θ_r, residue water content; Θ_s, saturated water content; K_s, saturated hydraulic conductivity.

The performance and evaluation of the HYPROP fit software was evaluated basing on the root mean square error (RMSE_TH) of the water content, root mean square of hydraulic conductivity (RMSE_k) and Akaike information criterion (AIC), for error prediction and the relative quality of fitting models for a given set of measured data. Table 4.3 summarizes the values of RMSE_TH, RMSE_K and AIC for the soil layers 0-30 cm with RMSE_TH values of 0.0075, 0.0084 and 0.0086 corresponding to 0-10, 10-20 and 20-30 cm soil layers. All the values are close to zero and therefore provides the satisfactory and very good performance the HYPROP fit software in estimation of soil retention characteristics and hydraulic parameters.

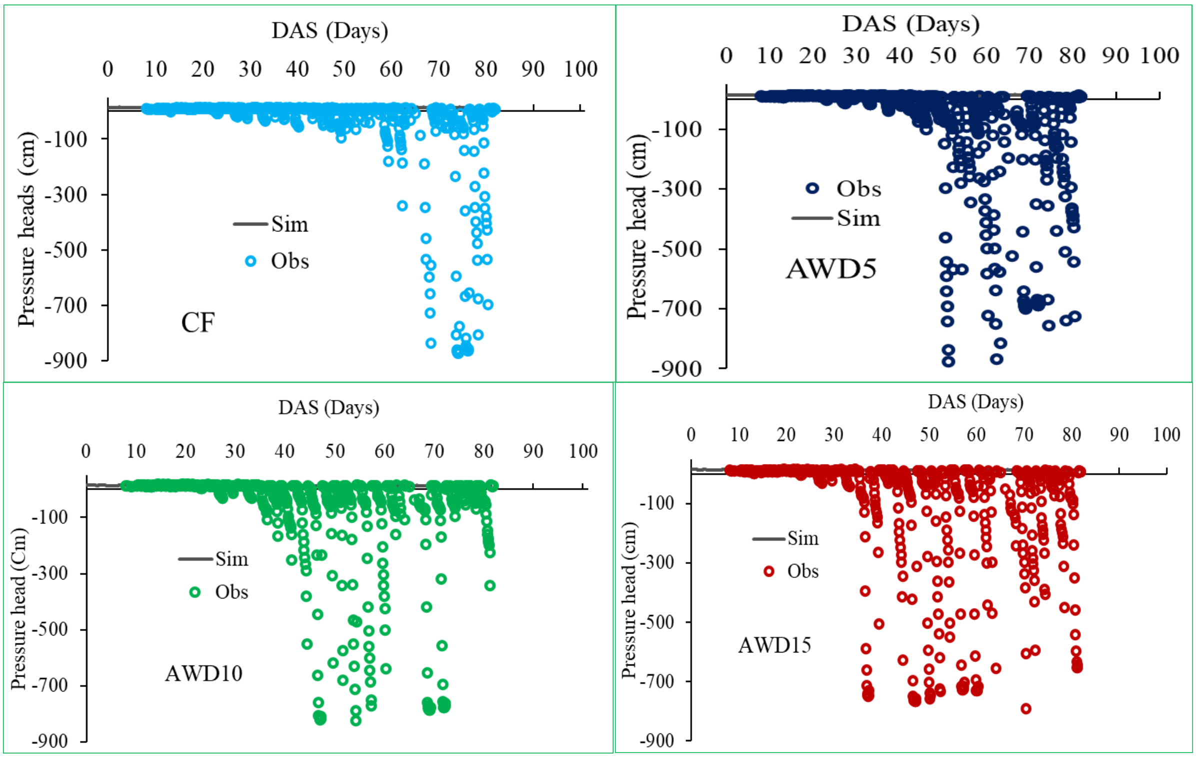
Table 4. 3: Performance evaluation of hydraulic and retention parameters

Soil profile	**RMSE_TH**	**RMSE_K**	**AICc**
0-10 cm	0.0075	0.1569	-1570
10-20 cm	0.0084	0.2329	-1415
20-30 cm	0.0086	0.0990	-2004

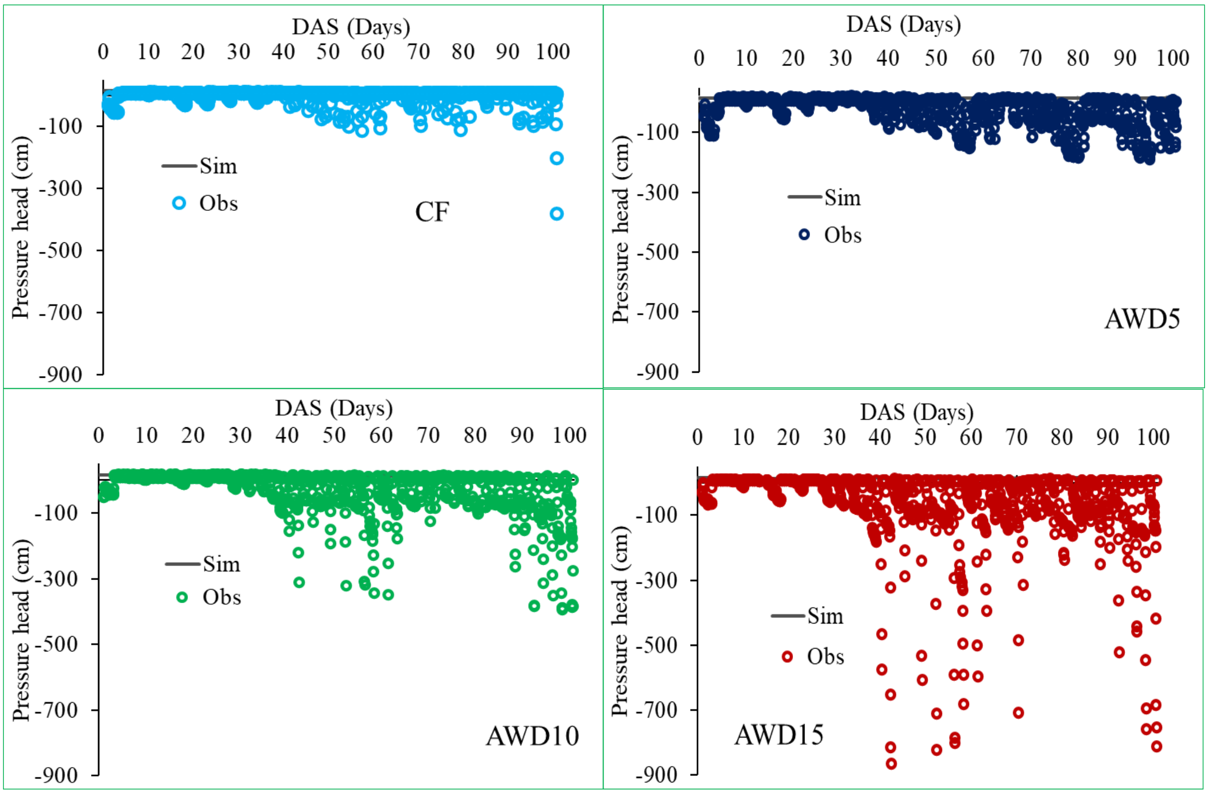
4.6.2: Simulated Pressure Head with Potential ET, PM-FAO Method

HYDRUS-1D model is a good and reliable tool to model water flow in rice paddy fields (Sutanto et al., 2012). In this research we evaluated the effectiveness of HYDRUS-1D for simulation of water flow and water balance components of directed seeded pot paddy rice cultivation in the closed system—phytotron. Using the soil hydraulic parameters estimated by Hyprop method in laboratory (Table 4.2) as initial estimates were used to simulate the pressure heads (Figure 4.12). Figure 4.12 shows the variation of soil pressure heads under different water regimes. The simulated pressure heads in both seasons indicate wet soil conditions throughout the cultivation period due to low estimated ET using PM-FAO method. Additionally, the observed pressure heads show negative pressure in all water regimes, even in CF. This variation in pressured head is corresponding to the crop stage and is proportional to the water regimes (Fig. 3.14), indicating soil drying conditions during crop growth.

The soil drying conditions were due to different water regimes, crop density and the crop growth stage —vegetative and maturity stages, related to high root water uptake. This was influenced by crop density and small size of the pots resulting in frequent soil drying and frequency cycles. Therefore estimation of ET by PM-FAO was inadequate and required adjusting the potential ET values in PHYDRUS-1D to improve on the simulation of the hydrological processes.



a) Season 1



b) Season 2

Figure 4. 12: Observed and simulated pressure heads during seasons 1 and 2.

4.6.5. Water Balance Components with ET, PM-FAO

The simulated water balance components at 10 cm depth of the soil profile are summarized in Table 4.4. The total irrigation under different water regimes during season 1 were 198.48, 162.89 and 122.22 cm corresponding to CF, AWD5, AWD10 and AWD15, respectively while during season 2 were 248.65, 205.77, 208.86 and 202.23 cm. The simulated evapotranspiration accounted for between 9.1 to 14.7 % of total water applied during season 1 and between 7.39 to 9.67 % in season 2. Generally the simulated evapotranspiration was low, although was slightly higher in season 2 than season 1 under different water regimes. The total water balance error varied between -0.03 to 0.07 during season 1 accounting for between 0.14 to 0.43 % of the actual irrigation and between 5.57 to 6.11 accounting for between 21.8 to 26 % of the irrigation in season 2.

Additionally evaporation and transpiration are the two water balance components with pot experiments. However, HYDRUS-1D simulations indicated that over 70% and 85% of the total irrigation in season 1 and 2 respectively was surface runoff. Considering the pot cultivation conditions, the high runoff was due to low estimated ET using PM-FAO method. Therefore adjusting the ET values using either empirical models or pot area relationship has been considered. While acknowledging HYDRUS-1D tool, simulated pressured head values (Fig. 4.12) were not good compared to observed values indicating that the soils were generally wet. Further from 38 DAS till harvest, the observed pressure head values show low negative pressure, an indication of soil drying conditions corresponding to growth stage and crop density, attributed to the root growth and the crop density restricted to the small size of the pots causing frequent water applications. Improving HYDRUS-1D model results required calibrations/fitting the soil hydraulic parameters and adjusting the potential ET values to correspond to soil conditions due to the crop density (section 4.5).

Table 4. 4: Simulated water balance components with using ET, PM-FAO Method.

	Water Regimes	Ia (cm)	Ea (cm)	Ta(cm)	SR (cm)	ΔS (cm)	WP (Kg/L)
Season1	CF	198.480	7.732	10.283	140.760	0.000	3.07
	AWD5	167.980	7.732	10.283	140.760	0.000	3.46
	AWD10	122.220	7.693	9.924	106.220	0.000	3.89
	AWD15	122.220	7.725	10.258	102.150	0.000	3.67
Season 2	CF	248.650	5.380	12.494	228.790	0.000	1.327
	AWD5	205.770	5.380	12.560	184.470	0.000	1.509
	AWD10	208.860	5.380	12.571	197.380	0.000	1.470
	AWD15	202.230	5.380	12.590	180.210	0.000	1.500

Note: Water productivity in season 1 was estimated based on the fresh grain yields after harvest compared to the water productivity in season was based on dry grain yields after dehusking. Where R; Rainfall, Ia;

Actual Irrigation, Ea; Actual Evaporation, Ta; Actual transpiration, ∆S; Change in soil water storage, ∑-total water balance error, Wp; ration of grain yield to irrigation amount and WPET; ration of grain yield to crop ET.

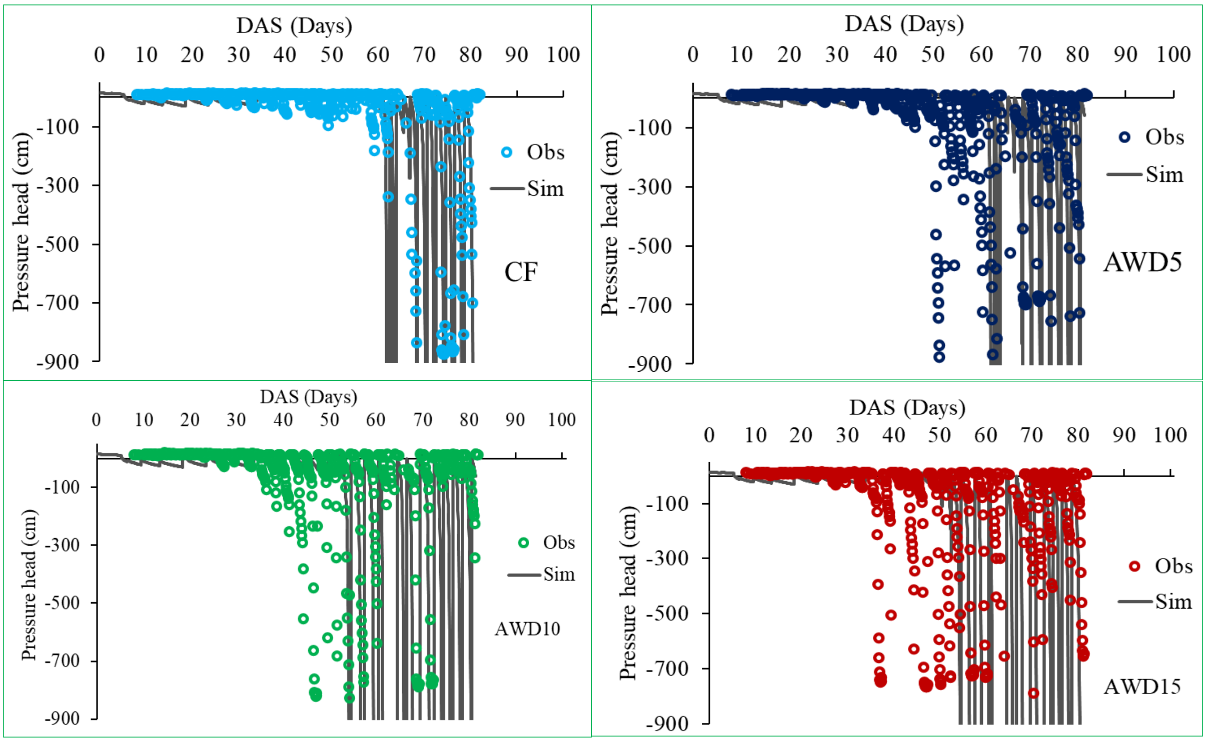
4.6.6: Simulated Pressured Heads with Adjusted ET in HYDRUS-1D

The simulated and observed pressure heads (Figure 4.12) with estimated ET using PM-FAO method showed saturated soil conditions throughout the whole cultivation period (Figure 4.12). Additionally, the simulated water balance components produced high over 70% and 85% surface runoff in season 1 and 2. Therefore fitting soil hydraulic parameters (k with l=0.5 for most soils) and adjusting potential ET was done to enhance the HYDRUS-1D performance. The soil hydraulic parameter, Ks were fitted using the inverse function of HYDRUS-1D model using the observed pressured heads for AWD15 in season 1, which were used in forward simulations in rest of the water regimes in both seasons. Similarly the potential Ep and Tp were adjusted from for the whole pot paddy rice cultivation period in both seasons (Figure 4.3).

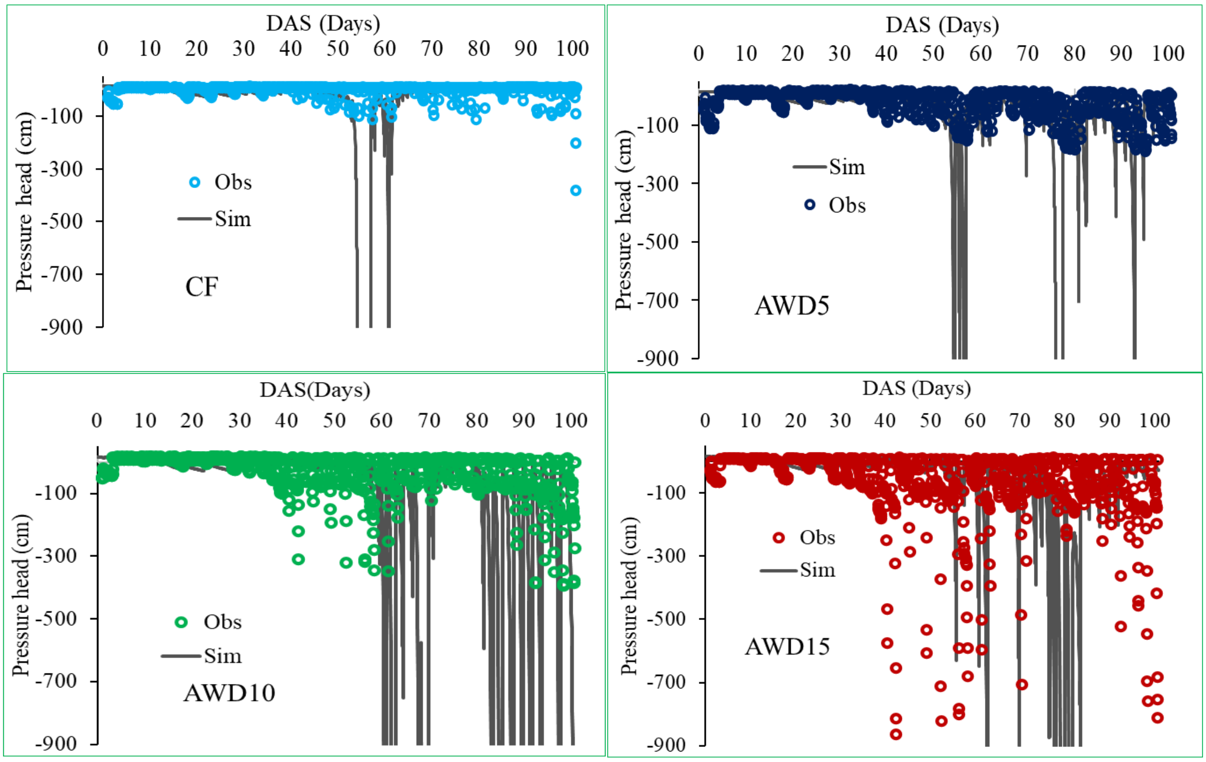
The HYDRUS-1D simulated pressured heads which varied quantitively compared to the observed pressure heads in both seasons (Figure 4.13). Besides the correspondence observed and simulated values were similarly good with CF in season 2 with over simulation of pressure heads in the rest of other water regimes (Figure 4.13). The low simulated pressure was a result of high adjusted potential ET particularly transpiration. The potential ETp was found to be 10 times higher than the estimated ETp using PM-FAO method. There are reasons to doubt the mismatch of observed pressure heads and simulated values due to; i) uniform measured the pressure heads at the same depth in all water regimes, yet the irrigation conditions were different, ii) changes in clay soil conditions—observed crack formation, swelling ad shrinkage contributing to variation in actual soil depth and iii) difference between the actual and measured water level in pressure and delay in water application. This is due to inability to know when water dropped to the required water level. The irrigation in AWD5, 10 and 15 regimes were applied water dropped to -5, 10 and -15 cm soil depth (Figure 3.6) while in CF when the ponded water dropped to zero cm on the ground surface.

During the first 35 DAS of crop growth the observed and simulated pressure heads was generally high compared to the rest of the cultivation period, indication of the wet soil conditions since the crops have not developed many roots —root water uptake (RWU) is low compared to evaporation. This is the reverse in the rest of other DAS during cultivation seasons. The low-pressure heads during the rest of DAS in both seasons, in vegetative and maturity crop stages were influenced by crop density and root growth causing high irrigation frequency, that produced changes between soil drying and wetting conditions. The observed pressure up to -

900 cm in all water regimes in season 2 while the same case in AWD15. However, these changes in the pressure head during soil drying conditions could not cause crop wilting even in AWD conditions from 21 DAS throughout whole crop cultivation as opposed to IRR recommendations (Bwire et al. 2021).



a) Season 1



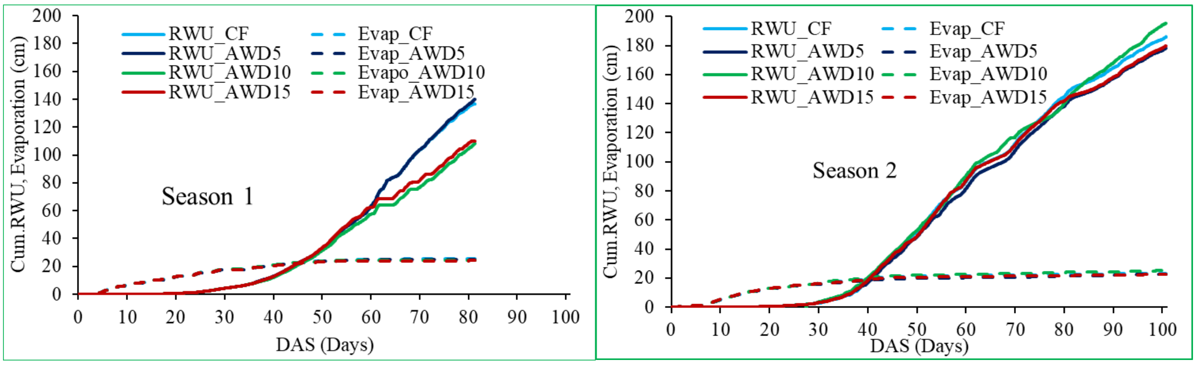
b) Season 2

Figure 4. 13: Observed and simulated pressure heads during season 1 and 2 with Adjusted ET

4.6.7 Simulated RWU and Evaporation with Adjusted ET

Figure 4.14 show variation of daily root water uptake (RWU) and evaporation (Evap) during the paddy rice cultivation for two seasons, simulated using HYDRUS-1D. Initially the root water uptake was nearly to zero at seed germination stage. RWU gradually increased after 28 and 30 DAS during season 1 and 2 respectively, reflecting crop growth, and reached maximum values between 56 and 69 DAS during season 1 and between 50-65 DAS in season 2. The maximum root water uptake reached approximately 2.35 cm/day around 61 DAS in season 1 and 1.35 cm/day around 55 DAS. During the later crop growth stage, daily root water uptake decreased substantially (Figure not shown). The cumulative root water uptake increased gradually after 27 and 30 DAS in season 1 and 2 respectively and then quickly increased and reached between 108.40 to 140.19 cm during season 1 and between 178.38 to 195.33 cm during season 2. The simulated RWU with adjusted ET values in HYRUS-1D during both seasons is over 10 times high compared to the simulated RWU with estimated ET using PM-FAO method.

Similarly evaporation is evident in both seasons with a high percentage during the early crop growth stages from 1 to 35 DAS. The simulated cumulative evaporation rates (Table 4.4) varied between 24.09 to 25.40 cm during season 1 and between 22.63 to 25.09 cm in season 2. In all seasons, the simulated RWU was within close range among the different water regimes with negligible differences between CF and AWD regimes, and among AWD regimes (Table 4.4). The difference in water regimes influenced crop growth with no significant differences on crop yields between CF and AWD regimes (Chapter 3). Promotion of AWD irrigation practice has potential of increasing paddy rice production, yields and water productivity under climate change (Bwire et al., 2021).



Where RWU; root water uptake, Evap; Evaporation

Figure 4. 14: Simulated root water uptake and evaporation with Adjusted ET.

4.7.3. Water Balance Components with Adjusted ET

The simulated components of the water balance at pot scale are presented in Table 4.6. The total irrigation under different water regimes during season 1 were 198.48, 162.89 and 122.22 cm corresponding to CF, AWD5, AWD10 and AWD15, respectively while during season 2 were 248.65, 205.77, 208.86 and 202.23 cm. The simulated evapotranspiration in season 1 accounted for between 81.66 to 100% of total water input under different water regimes in season 1 and between 84.22 to 100 % in season 2. Simulated evapotranspiration was within close range in both seasons, with slight difference among the regions in season 1 and 2. The total water balance error accounts for between 2.45 to 6.3 % during season 1 and between 0.69 to 4.65 % of the actual water applied during season 2.

The errors during season 1 and 2 with adjusted ET in HYDRUS-1D provide a reasonable indication that HYDRUS-1D is good tool for simulating the water balance components. While acknowledging HYDRUS-1D tool, carrying out sensitivity analysis and improving fitting of soil hydraulic parameters would enhance HYDRUS-1D simulation. Further the simulated low-pressure heads shows that the soils were generally dry in all water attributed to the root growth and the crop density restricted to the small size of the pots causing frequent water applications.

Additionally the average pot grain yield in season 1 and 2 varied from 0.27, 0.27, 0.23 Kg from fresh grain yield, and while in season 2 average dry grain yield were 0.16, 0.15, 0.15 and 0.14 Kg corresponding to CF, AWD5, AWD10 and AWD15 respectively. The grain yields of the directly seeded rice paddy were mostly influenced by the climatic conditions within greenhouse, the pot sizes, crop density, irrigation regimes and fertilizer application. Water productivity, referred to as Water use efficiency, is a function of crop yields and water applied in given season (Li et al., 2014). Water productivity was computed: irrigation water productivity (WP)—ratio of grain yield to the irrigation water amount (Sudhir-Yadav et al., 2011). The ET was estimated as summation of Ep and Tp during the entire seasons as simulated in HYDDRUS-1D model. The difference between WP values in both seasons is attributed to different irrigation amounts. The WP during season 1 with fresh yields after harvest was 3.07, 3.47, 3.89 and 3.67 Kg/m^3 while in season 2 with dry grain yields was 1.33, 1.51, 1.47 and 1.50 Kg/m^3 corresponding to the CF, AWD5, AWD10 and AWD15 water regimes. These values are closely related to research value (1.6 Kg/m^3) reported by Sudhir-Yadav et al., (2011) in India for intermittently and daily directly seeded rice (DSR). The estimated water productivity indicates that AWD regimes with DSR conditions in both seasons had better water use efficiency compared to CF, made sufficient use of irrigation water. Similarly water productivities in both seasons with respect to simulated evapotranspiration (Ea and Ia) indicates that the yields are strongly related to the RWU under different water regimes.

Table 4. 5: The simulated water balance components during seasons 1 and 2

Water Regimes		Ia (cm)	Ea (cm)	Ta(cm)	SR (cm)	ΔS (cm)	∑	∑,%	WP (Kg/m^3)
Season1	CF	198.480	25.400	136.670	12.319	-9.742			3.07
	AWD5	167.980	25.208	140.190	11.826	-5.130	-4.119	2.452	3.46
	AWD10	122.220	24.630	108.40	2.190	-5.300	-7.700	6.297	3.89
	AWD15	122.220	24.090	110.220	1.630	-9.420	-4.300	3.500	3.67
Season 2	CF	248.647	23.340	186.07	28.088	0.000		4.650	1.327
	AWD5	205.770	22.659	178.380	4.073	-0.767	1.425	0.693	1.509
	AWD10	208.864	25.093	195.330	4.362	-8.622	7.300	3.495	1.470
	AWD15	202.230	22.625	180.000	4.362	-1.268	3.760	1.859	1.500

Note: Water productivity in season 1 was estimated based on the fresh grain yields after harvest compared to the water productivity in season was based on dry grain yields after dehusking. Where R; Rainfall, Ia; Actual Irrigation, Ea; Actual Evaporation, Ta; Actual transpiration, ΔS; Change in soil water storage, ∑- total water balance error, Wp; ration of grain yield to irrigation amount and WPET; ration of grain yield to crop ET.

4.7 Summary

In this chapter, water flow and soil water balance components in DSR of paddy rice pot experiment under AWD regimes was evaluated using HYDRUS-1D for two seasons. HDRUS-1D simulations using the ET by PM-FAO method produced saturated conditions and runoff, an indication that PM-FAO was inadequate to estimate ET in such a closed system with pot paddy rice cultivation. The irrigation frequency at early crop growth stage (within 35 DAS), when crops have less roots, the environmental surface boundary conditions are influenced by evaporation during both seasons resulted into more wet soil conditions—pressure heads compared to the rest of the crop growth stages. At the early crop growth stage, the wetting conditions is due to relatively low hydraulic conductivity and after 34 DAS when the crops roots are developed, more irrigation frequencies were observed, influenced by crop growth, crop density and pot size creating more soil drying conditions due to change in soil hydraulic conductivity. Additionally, soil drying was evident by several crack formations in pots (observed during field monitoring), affecting soil hydraulic conductivity and irrigation water application. Water productivity evaluated based on total irrigation water input elucidates the differences in water use efficiency comparing CF and AWD regimes in DSR during both seasons.

Similarly, irrigation frequencies in 30 DAS with adjusted ET values during both seasons were higher than evaporation which contributed to soil wetting conditions. Considering HYDRUS-1D model requires more input data, it was able to analyze the crop and soil processes—infiltration, surface fluxes, root water uptake and evaporation in paddy pot experiments with different water management methods. However, adjusting potential ET in HYDRUS-1D could not produce a straightforward relationship between simulated and observed pressure heads. These varied quantitively with low simulated pressure heads compared to observed values, due to soil drying and RWU was over 10 times high than the RWU simulated with ET using PM-FAO method. It was not easy to simulate water flow hydrological processes during the crop growth.

The study has shown high water productivities in all AWD regimes compared to CF for both seasons without significant effect of crop growth and yield, though with negligible yield differences. Adoption of AWD irrigation in developing countries needs to be emphasized to enhance water saving and increase paddy rice production with climate change.

Chap. 5: Evaluation of Deficit Irrigation Scenarios on Paddy Rice Root Water Uptake for Water Management in Uganda

5.1. Background

Rice (*Oryza sativa L.*) is a staple food and cash crop among smallholder farmers. It plays a significant role in ensuring food security and economic stability in Uganda, making it the second most important cereal after maize (Hong et al., 2021). Over the last decade, rice production and expansions in Uganda have increased annually at an average rate of 7.33%, prompting the government and development agencies to develop promotional initiatives (Bwire et al. 2022a). Additionally, rice cultivation typically involves flooding paddy fields, requiring more water and contributing to greenhouse gas emissions, especially methene. This traditional method is resource-intensive and environmentally unsustainable, especially in the face of climate change, contributing to water scarcity (Bwire et al. 2022b).

However, the current rice production records are still low, between 3.6 t/ha to 1.7t/ha, especially in Uganda, against the potential 5 t/ha in eastern and northern Uganda (Hong et al., 2021). Factors contributing to low rice production include climate changes resulting in high temperatures and droughts and low irrigation systems development (Bwire et al., 2022a).

Promotion and adoption of agricultural water management strategies for paddy rice fields must be emphasized in Africa and Uganda in particular. Different deficit water management techniques have been proposed to enhance water management in paddy rice for increased yields amidst dwindling water resources and climate change. AWD regimes are closely related to deficit irrigation scenarios in which several research indicated that the technology could save up to 30 % water without a significant decrease in yield compared to continuous flooding, making it suitable for paddy rice expansion (Ishfaqa et al., 2020).

However, applying such water climate-smart water management techniques requires a thorough, in-depth understanding of rice root water uptake (RWU). To partly achieve this, the HYDRUS-1D model, a widely recognized and well-established tool for simulating water flow and solute transport in the vadose zone was used (Simunek et al., 2012). Applying the model to study the RWU under different deficit irrigation scenarios is vital in understanding various hydrological processes—evaporation, transpiration, fluxes, and water stress. This forms a guide in developing efficient water management technologies for optimal water use in paddy rice fields.

While appreciating that HYDRUS-1D model can evaluate deficit irrigation scenarios, the practical field application of the irrigation scenarios requires developing smart water application systems such as use of digital agriculture, where the Internet of Things (IoT) is an emerging virgin concept. The IoT offers a unique opportunity to monitor, control, and optimize water management in agricultural systems. Uganda has a rich agricultural tradition and a growing tech sector which can benefit greatly with the integration of IoT innovations into irrigation systems, including AWD practice for water management. Designing an IoT GSM-based system is significant to improving precision irrigation for increased crop yields, and economic benefits for farmers.

The objective of this chapter was to evaluate deficit irrigation scenarios on paddy rice root water uptake and their effect on water use, crop yields and other soil hydraulic parameters. Additionally, develop and test the IoT smart system for pilot agricultural water management in paddy fields in Uganda.

5.2. Methodology

5.2.1. Pilot Study Area in Uganda

Uganda is among the leading countries in rice production in East Africa, with the rice production by smallholder farmers and few rice schemes. Developing water management approaches with climate change including deficit irrigation scenarios for increasing paddy rice productivity in large schemes such as for Doho rice scheme (Figure 5.2) in important aspect in of this chapter. The scheme is in Butaleja district of Eastern Uganda (Figure 6.1) between altitudes of 1,100 to 1,220 m with Longitude 34°02' E and Latitude 0°88' N within Lake Kyoga basin covering an area of 494.2 km2 with about 4,340 farmers growing rice (Muhindo et al. 2023). Doho rice scheme was developed in 1976 by the Chines government to respond to the farmers need. It's the largest irrigation scheme in Uganda that covers an area of 1000 ha with close to 3840 beneficiary farmers and 11 irrigation blocks drawing water from R. Manafwa with each block having 8–30 strips, and each strip with between 4 and 80 plots (Ayella et al., 2022). The main channel provides irrigation water from the Manafwa River to the scheme (Bwambale eta al., 2019).

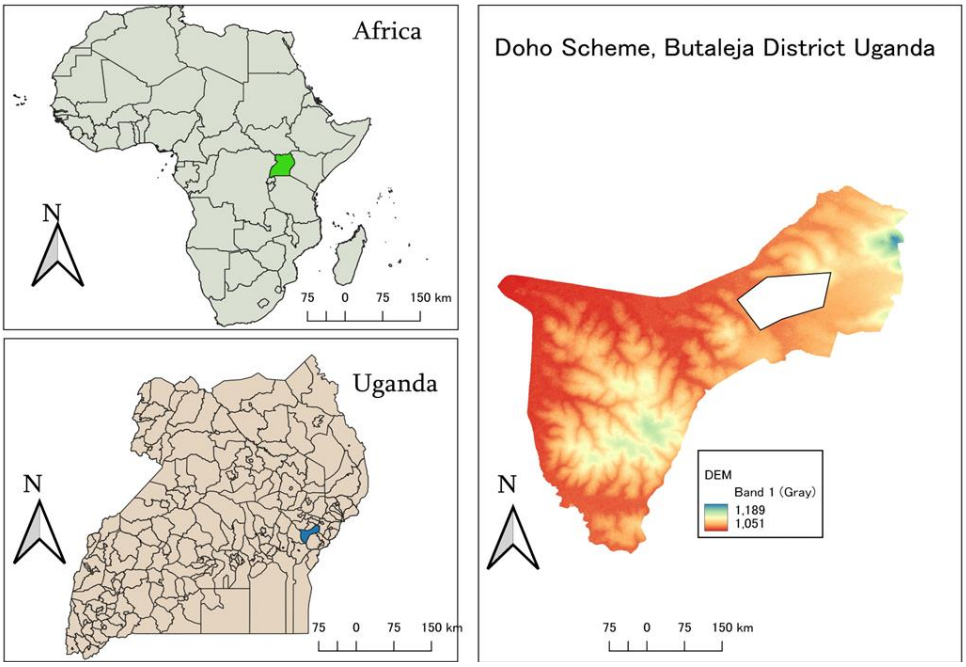
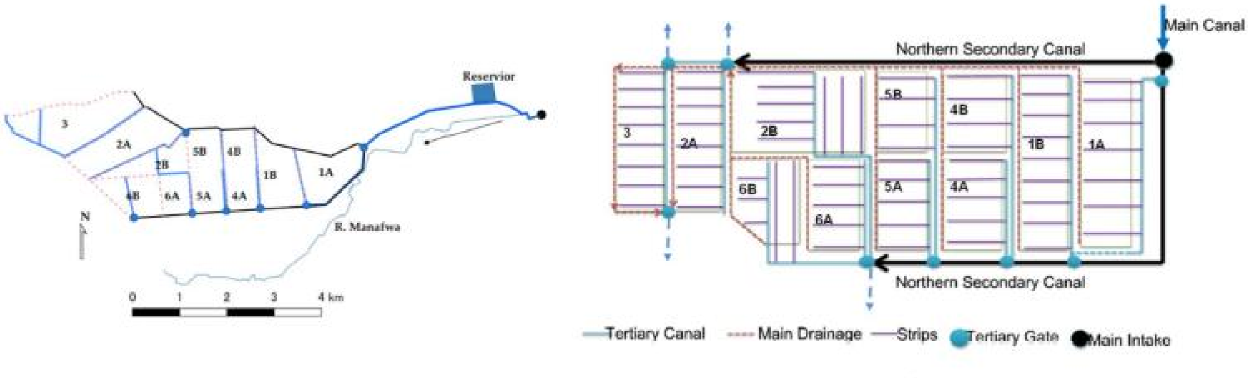


Figure 5. 1: The geographical location of Doho rice scheme in Uganda**.**



(a) (b)

Figure 5. 2: The (a) actual layout of the Doho rice scheme and (b) schematic layout. The strip is the last terminal canal—source: Ayella et al., 2022.

5.2.2. Climate Characteristics and Rice Cultivation Calendar

Doho rice scheme experiences a tropical climate with a temperature range of 16 to 32^{0}C and annual rainfall range of 750 to 1500 mm. The area has a bimodal rainfall pattern with peaks from March to May and October to November (short rainfall period). These correspond to the two rice cultivation seasons in the scheme and Uganda with the first rice season from March to August and the second from October to February. Figure 5.3 a and b show the changes in climatic conditions around the scheme over the last decade.

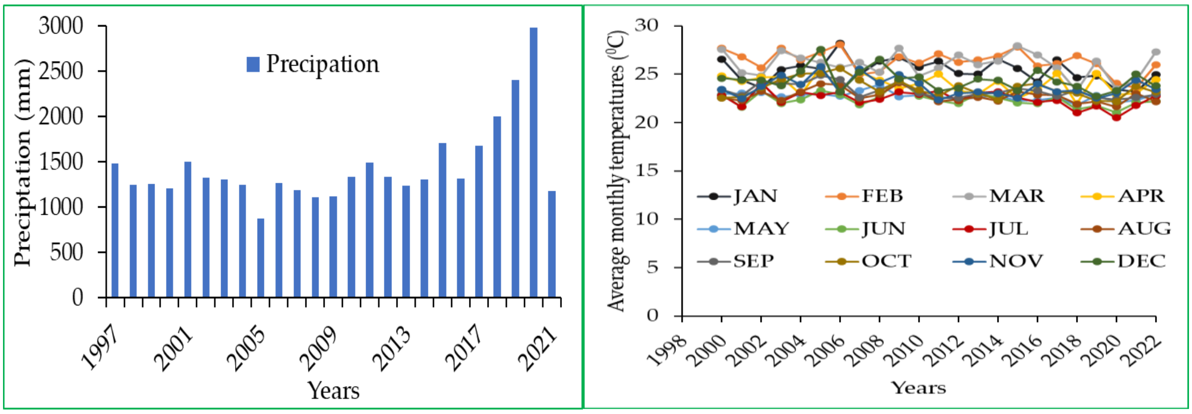
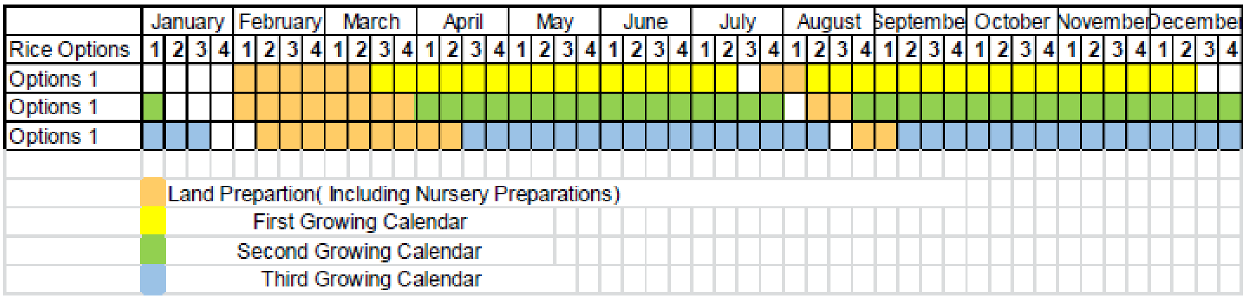


Figure 5. 3: Annual changes in a) precipitation and b) monthly temperature in Doho rice scheme for 25 years;1997-2021. Data source: NASA (https://power.larc.nasa.gov/data-access-viewer/).

With enough precipitation, annual rice cultivation is possible. However, the area is experiencing climate changes contributing to a decline in precipitation and drought periods, especially from June to September and December in some cases. These changes are among the factors contributing to low rice yields in the country.

Rice is an emerging crop grown for cash and household consumption in Uganda. Total annual rice production is estimated at 165,000 metric tons while total rice consumption is estimated at 350,000 metric tons, leaving the country with deficit in rice supply covered through imports (Hong et al., 2021). Several lowland and upland rice varieties are cultivated within the scheme including and not limited to NERICA 1, 4 & 10, TDX305 (Supa), K85 (Kaiso), NamChe, Sindano, K98 (Supa China), K95 (Nylon), Kibuyu, Benenego and Supa America (IR64). The average

Table 5. 1: Annual rice cultivation calender in Uganda. Source: Ayella et al., 2022.



	January				February				March				April				May				June			
Rice Options	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Options 1					🟧	🟧	🟧	🟧	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Options 1	🟩				🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Options 1	🟦	🟦	🟦			🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

	July				August				Septembe				October				Novembe				Decembe			
Rice Options	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Options 1	🟨	🟨		🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
Options 1	🟩	🟩	🟩	🟩		🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Options 1	🟦	🟦	🟦	🟦	🟦	🟦		🟧	🟧	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟧 Land Prepartion(Including Nursery Preparations)
🟨 First Growing Calendar
🟩 Second Growing Calendar
🟦 Third Growing Calendar

5.2.3. Defining Deficit Irrigation Scenarios and Assumptions

Paddy fields have a high percentage of clay soil content, as with the Doho Scheme in Uganda. Considering this fact, the deficit irrigation scenarios were developed based on the irrigation water application of previous experimental data for the continuous flooding method (CF)—a control treatment during the first two seasons (Figure 6.4). The pot paddy rice experiment was carried out in greenhouse conditions, Tokyo University of Agriculture and Technology described in chapter 3. Irrigation water with CF treatment was applied to 5 cm ponding whenever ponded water reached zero water level on the ground surface. This was defined as full irrigation in the scenario analysis.

i. Suitability of full irrigation water management (CF): Comparative analysis of full irrigation continuous flooding (CF) irrigation in paddy rice and different defined deficit irrigation scenarios for optimal root water uptake (transpiration), water use and without affecting crop growth and yields.
ii. We defined deficit irrigation scenarios by altering CF's irrigation water amounts (TWA) by 80, 60 and 40%—saving water by 20, 40 and 60% while maintaining the irrigation frequency of the CF for the two seasons (Table 5.1), applied throughout the whole paddy rice cultivation period.
iii. Evaluate the effect of deficit irrigation scenarios on RWU using HYDRUS-1D Model.
iv. Develop IoT based system for pilot of irrigation scenario to enhance precision irrigation water management in Uganda.

Table 5. 2: Defined deficit irrigation scenarios

Irrigation Scenarios	Descriptions	Details
A_1	Continuous Flooding (CF)	Water application based on CF from previous experiments 1 and 2
A_2	80_TWA (%) condition	Defines 80% applied irrigation water of CF. j-describes the four crop stages: Crop development, canopy grow maximum canopy and maturity stage
A_3	60_TWA (%) Condition	Defines 60% applied irrigation water of CF. j-describes the four crop stages: Crop development, canopy grow maximum canopy and maturity stage
A_4	40_TWA (%) Condition	Defines 40% applied irrigation water of CF. j-describes the four crop stages: Crop development, canopy grow maximum canopy and maturity stage

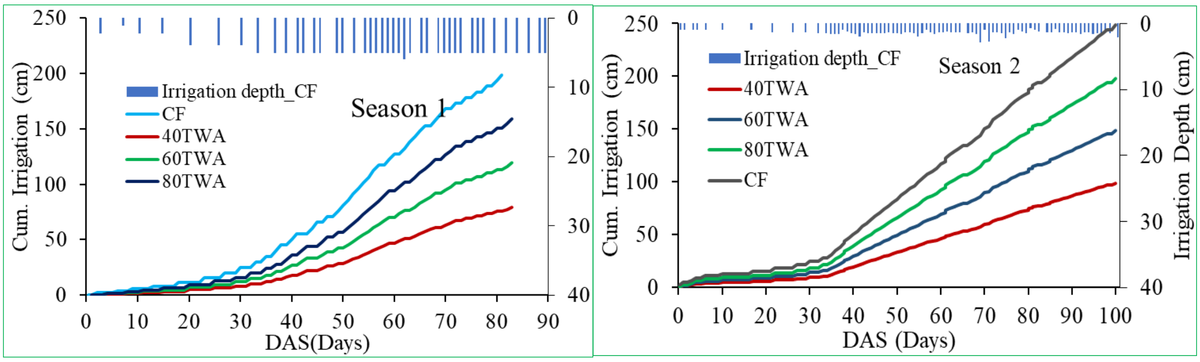


Figure 5. 4: Cumulative applied irrigation water under defined irrigation scenarios.

5.2.4. Simulation of Deficit Irrigation Scenarios in HYDRUS-1D Model

Simulation of different irrigation management scenarios was performed using HYDRUS-1D model. HYDRUS-1D numerically solves the Richards equation using Galerkin finite-element schemes defined. The details of HYDRUS-1D model equations are described in Chapter 4, section 4.3.

The simulation soil profile was small using the experimental data for two seasons in chapter 4. Therefore water flow in the soil profile from the soil surface to the bottom surface of the pots was predominantly in the vertical direction, and horizontal flow in the ponding surface layer or irrigation, can be accounted for using boundary conditions. The adjusted potential evapotranspiration for the two seasons was adopted in this simulation (Figure 6.5).

Root water uptake, a sink term in Richards's equation, is the volume of water removed from a unit volume of soil per unit time by the plant defined by Feddes equation (Feddes et al., 1978).

$$S(h) = \alpha(h) \times S_p \tag{5.1}$$

Where S_p is the potential water uptake (cm^3/cm^3/day) and $\alpha(h)$ is the reduction term of the root water uptake function generally taking from 0 to 1. The method to consider water stress was used to determine root water uptake. The Feddes model parameter values optimized by Singh et al. (2003) for rice crops (h_1= 100 cm, h_2= 55 cm, h_3 (high) = −160 cm, h_3 (low) = −250 cm, and h_4= −15,000 cm) were used to parameterize the water stress response function proposed by Feddes et al. (1978) and Homaee et al. (2002). Parameters h_1 through h_4 represent different pressure head values, which affect root water uptake in the soil.

The irrigation scenarios were defined from the experiment data under full irrigation (CF) for the two seasons with pot paddy rice cultivation. The initial and boundary conditions for deficit irrigation scenario simulations were defined as in chapter 4.

5.3 Development of IoT Smart System for Agricultural Water Management

Increasing drought is a major factor contributing to water scarcity and water management is a crucial concern in water scarce areas. This coupled with diminishing natural resources, arable land, and unpredictable climatic conditions makes food security a global concern (Elijah et al, 2018). Agriculture is the main consumer of freshwater while traditional paddy cultivation systems in Uganda faces several challenges—field water loss, a need for intense labor with high percentages of women, inadequate technology knowledge at farm level (Lebdi, 2016), etc. Alternate wetting and drying Irrigation (AWD) technology with paddy rice cultivation has its limitation including the mismatch of water applications based on matric potential and water level, frequent field monitoring and discrepancy between actual water level—time when water dropped to the defined water table and measured water level, varying with soil type and conditions (chapter 1, 2 and 3). The internet of things (IoT) emerges as a natural choice for smart water management (Carlos et al, 2019). The ecosystem of the IoT smart systems with AWD technology has been developed, though still under modifications (Figure 5.5).

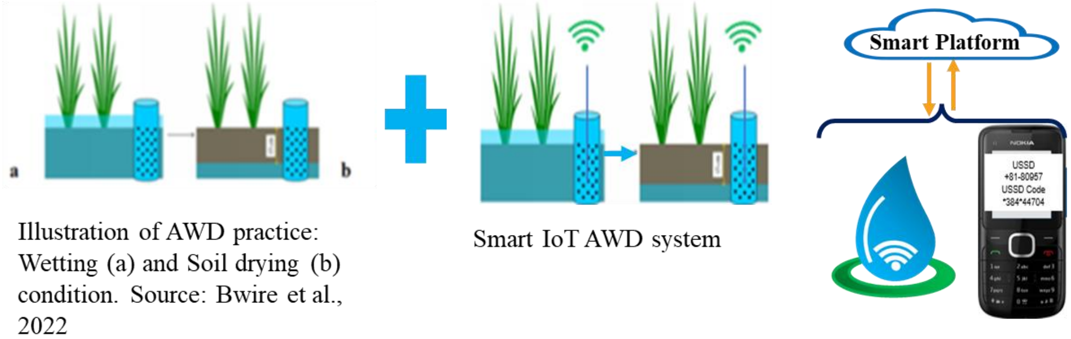


Illustration of AWD practice: Wetting (a) and Soil drying (b) condition. Source: Bwire et al., 2022

Smart IoT AWD system

App & Code

Figure 5. 5: Illustration of the ecosystem of IoT smart system for paddy rice field

5.4. Results and Discussions

5.4.1. Simulated Root Water Uptake and Evaporation

The simulated root water uptake (RWU) accounted for 68.86, 71.25, 69.40 and 69.91 % of the total irrigation water corresponding to CF, 80TWA, 60TWA, and 40TWA irrigation scenarios using data on total water applied (TWA) in season. Similarly the RWU during season 2 accounted for 75.44, 84.02, 87.35 and 87.90 % corresponding to CF, 80, 60 and 40TWA. The simulations of the different irrigation scenarios showed evaporation decreased with crop growth during the crop cultivation while the RWU increased with crop growth stage and irrigation amounts.

Figure 5.6 shows the variation of paddy rice's daily root water uptake and evaporation during the two seasons, simulated using HYDRUS-1D. Initially, the root water uptake was close to zero at the seed germination stage. RWU gradually increased 28 and 30 DAS during season 1 and 2 respectively reflecting crop growth, and root growth. The maximum root water uptake was approximately 2.184 cm/day under CF (full irrigation) at around 62 DAS in season 1 with neglectable differences of 0.012, 0.008 and 0.00 cm/day compared to 40TWA, 60TWA, and 80TWA, respectively. Additionally, the maximum RWU in season 2 was the same in all irrigation scenarios, with an average value of 1.07 cm/day around 56 DAS. During the later crop growth stage, daily root water uptake decreased substantially.

Most evaporation in both seasons occurred during the early crop growth stages up to 35 DAS. The simulated cumulative evaporation rates (Table 5.2) using HYDRUS-1D varied between 13.811 and 25.40 cm during season 1 with cumulative potential value of 44.45 cm. Similarly evaporation in season 2 varied between 16.42 to 23.34 with the cumulative potential value of 62.5168 cm. The simulated RWU and evaporation during all seasons varied proportionally to the deficit scenarios during both seasons, with negligible differences between full irrigation (CF) compared to 80TWA, 60TWA, and 40TWA irrigation scenarios.

The difference in RWU between full irrigation (CF) compared to 80TWA, 60TWA and 40TWA scenarios in both seasons was minimal and insignificant to cause water stress, crop wilting and cause significant yield reduction (Bwire et al., 2022). Being simulated case with HYDRUS-1D, pilot application of irrigation scenarios in Doho irrigation scheme, Uganda with IoT smart system is important. This could enhance rice productivity—reduce water use, save water by either 20, 40 or 60 % and enhance paddy rice yields.

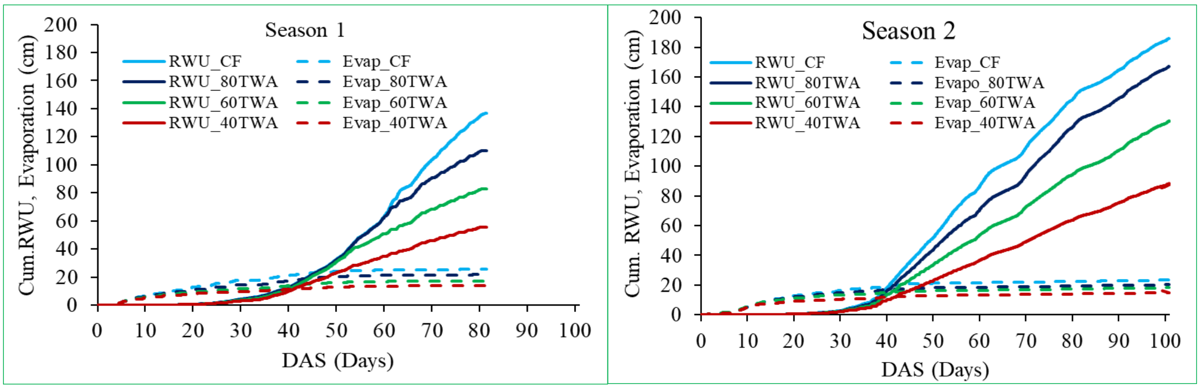


Figure 5. 6: Root water uptake under defined deficit Irrigation scenarios.

5.4.3. Simulated Water Balance Components under Deficit Scenarios

Water balance components under different irrigation scenarios were simulated as presented in Table 5.4. The simulated evapotranspiration in season 1 accounted for between 84.22 to 100 % of total water input under different irrigation scenarios and between 81.66 to 100 % in season 2 of the total water input. Simulated evapotranspiration was slightly higher in season 1 compared to season 2 under different irrigation scenarios. The simulated ET values showed that less irrigation was proportional to RWU, indicating crops can maximize water use efficiently with irrigation application.

Additionally simulated changes in water storage indicates water deficit in the soil under deficit scenarios with more deficits in season 1. Under deficit scenarios, crops able are able to utilize water efficiently.

Table 5. 3: Summary of simulated water balance components under deficit irrigation scenarios

Soil Water balance Components					
	Water Regimes	Ia (cm)	Ea (cm)	Ta(cm)	ΔS (cm)
Season1	CF	198.480	25.400	136.670	-9.742
	80TWA	158.840	21.631	110.280	-10.079
	60TWA	119.100	17.165	82.647	-10.287
	40TWA	79.390	13.811	55.498	-10.491
Season 2	CF	248.647	23.340	186.070	0.000
	80TWA	198.920	20.263	167.140	0.000
	60TWA	149.190	18.203	130.330	-7.106
	40TIWA	99.460	16.424	87.430	-9.873

Note: Ia; Actual Irrigation, Ea; Actual Evaporation, Ta; Actual transpiration, ΔS; Change in soil water storage.

5.5. Summary

Using the data of the total water applied for CF during seasons 1 and 2, deficit scenarios were simulated for pot paddy rice cultivation in HYRUS-1D model. The tool has demonstrated its effectiveness in evaluating root water uptake under deficit irrigation scenarios. Subsequent irrigation scenarios corresponding to full and deficit irrigations could be performed and extended in simulating fluxes for the two seasons. Deficit irrigation scenarios resulted in low fluxes and, therefore, low percolation rates for field conditions, which enhance water savings by up to 40%. Adopting deficit irrigation scenarios will reduce groundwater recharge and associated nutrient percolation.

Simulated water balance components—RWU, under deficit irrigation scenarios resulted in negligible difference in RWU during both seasons, saving water up to 40%. Considering the research findings and since this is simulated scenarios, it's important for the researcher to perform detail investigations of the deficit irrigation scenarios on hydrological processes and root growth—size (length and width) for optimal water use, rice productivity, and yield in Doho rice scheme in Uganda. The findings indicate the application/reduction of irrigation amounts while maintaining the irrigation frequency gave more RWU compared to CF in both seasons. However, the difference in simulated evapotranspiration under different deficit irrigation scenarios compared with CF in both seasons corresponded to deficit scenarios. Water productivity and water productivity are highly dependent on root water uptake.

Chap.6: Conclusion

6.1 General Conclusion

This study embarked on a journey to investigate the feasibility, effects, and benefits of Alternate Wetting and Drying (AWD) irrigation on paddy rice, practiced throughout the whole paddy rice cultivation period as opposed to IRRI. The background of this dissertation (chapters 1 and 2) is built on detailed literature synthesis on the global and regional (East Africa) concern of the increasing water scarcity, dwindling water resources, groundwater shrinkage and influence of climate change on rice production. The synthesized literature was taken from key scientific papers, technical reports, and other sources focused on the status of water management, irrigation development, rice cultivation, AWD practices, eco-hydrological processes, and food security issues in East Africa.

However, paddy rice is predominantly grown in wet conditions, whose eco-hydrological characteristics are impacted by water regimes. Paddy water requirements vary widely depending on field and crop stages—nursery, main field preparation, planting to panicle initiation, panicle initiation to flowering, and flowering to maturity corresponding to 40, 200, 458, 417 and 125 mm of water, respectively. Paddy management, especially puddling, significantly affects soil hydrological properties, such as hydraulic conductivity, percolation, and seepage in the paddy rhizosphere. Knowledge of these interactions is vital to enhance sustainable water management strategies in paddy fields. Promoting climate-smart agricultural technologies including alternate wetting and drying (AWD) and the Internet of Things (IoT), can enhance farmers' real-time decisions and improve water management for increased paddy yields and food security.

The effect of AWD regimes was assessed through paddy rice field experiments for three seasons (Feb/2021 to March/2022) on safe AWD regimes (AWD5, AWD10 & AWD15) as treatment defined when water level in observation tubes in paddy field dropped to -5, -10 and -15 cm blow the ground surface (AWD5, AWD10 and AWD15) and continuous flooding (CF) as control when water ponding dropped to zero cm on ground surface. The rice variety Ikuhikari, a short Japanese grain, was used in the pot rice cultivation experiment in glass greenhouse conditions at Tokyo University of Agriculture and Technology (Chapter 3). Quantitative evaluations of water flow, and soil water balance components (Chapter 4) and deficit irrigation scenarios (chapter 5) on root water uptake was performed using HYDRUS-1D. Additionally Internet of Things (IoT) smart water management system has been developed (Chapter 5).

Therefore, the conclusion summarizes the key research findings and recommendations for future related research for improving agricultural water management in paddy fields through a holistic and data-driven approach to increase paddy rice cultivation and crop water productivity for food security in East Africa under climate change.

6.1.2. Potential of AWD Irrigation and Rice Cultivation Experiments

The literature synthesis was performed to assess the potential of AWD technology in chapter 2. Similarly implementing AWD regimes and paddy rice cultivation experiment between February 2021 and March 2022, at TUAT, Japan, demonstrated that AWD irrigation is a practical and smart technique to reduce water usage and increase rice productivity. The empirical results observations, including agronomic data supported the effectiveness of the AWD technology and soil hydrological conditions—soil pressure head measurements demonstrated the variation in soil conditions. The findings of chapter 2 and chapter 3 are summarized below.

i. The region is facing climate related issues such as precipitation deficits, affecting water for rice production. Little is known about AWD technology in East Africa and the current practice of at micro-research level, leaving a gap to pilot the technology for rice production.

ii. Any water stress due to different water management at panicle and grain formation contributed to difference in crop growth and yields.

iii. AWD practice can be applicable throughout the whole rice cultivation with no significant grain yield reduction so long as the soil moisture is in the range of readily available water for the rice, depending on the soil type and soil hydraulic conditions.

iv. AWD demonstrated improved irrigation water productivity and water saving up to 36 % compared to CF, with insignificant differences in yields and increase the HI of paddy rice. Making it a sustainable solution to enhance paddy rice yields in water-scarce regions and with climate change.

v. Negative pressure heads proportional to the water regimes even with CF and up to -900 cm in AWD 15. This was attributed to high root water uptake influencing the duration of soil wetting and drying conditions under AWD regimes and irrigation frequency.

6.1.3. Simulated Hydrological Processes of AWD Regimes in Paddy Soils

Water flow and eco-hydrological processes vary with different water management conditions in paddy fields. HYDRUS-1D model simulated the interactions of the eco-hydrological processes, root water uptake, and other water balance components in directly seeded paddy rice (DSR) under different water regimes. The researcher observed the following remarks:

i. Saturated conditions in all water regimes due to low ET estimated by PM-FAO equation. The PM-FAO equation was inadequate to estimate ET in the closed system with pot rice cultivation.
ii. Potential ET in HYDRUS-1D was higher than ETp by PM-FAO by over 10 times due to overestimated Tp.
iii. It's not easy to simulate hydrological processes during crop growth. HYDRUS-1D simulated water balance component though the simulated pressure heads differed quantitatively with observed value since the observed pressure heads were measured at the same depths in all water regimes.
iv. Estimation of water balance components including ET is quite tricky with pot experiment since the crop's roots are restricted to the pot size and crop density and stage influence irrigation frequency.

6.1.4. Simulated Deficit Irrigation Scenarios and IoT System Design

Root water uptake (RWU), a critical hydrological process, that significantly influences irrigation water amount, frequency, and crop productivity, impacting total irrigation water application in paddy rice fields. This was simulated in HYDRUS-1D with defined deficit irrigation scenarios: CF, A_2, A_3, and A_4 corresponded to continuous flooding (full irrigation-CF), 40, 60 and 80 % of the data on total irrigation applied (TWA) for CF from experimental paddy rice cultivation. The following observations were made:

i. Simulated RWU was proportional to the irrigation scenarios since reducing total irrigation amounts defined by deficit irrigation regimes demonstrated high RWU compared to CF.
ii. Tools such as HYDRUS-1D can be applicable and useful to assess the deficit irrigation scenarios which is important in irrigation planning.

6.2 Recommendations and Future Directions

The research findings from this study have proved the need for future research work on agricultural water management. Agricultural water technologies including AWD irrigation technology and deficit irrigation scenarios can improve paddy rice productivity for food security in East Africa. Knowledge gaps on AWD technology application—relationship between matric potential and field water level (FWL) with safe AWD practice throughout the whole cultivation is still wanting.

Based on the research findings, it's important for the researcher to perform detail investigations of AWD practice and the deficit irrigation scenarios in field conditions in Africa—Uganda. Further evaluate soil hydrological conditions and water balance components of transpiration and root growth—size (length and width) and optimal roots depth for effective crop growth and yield in field relationships. The cumulative RWU in CF and deficit scenarios 80TWA, 60TWA and 40TWA was proportional to reduction in water applied during both seasons. Although field investigation of these scenarios in field conditions is vital to understand whether application of irrigation up to 40% would not affect agronomic performance of the paddy rice. This is evidence that HYDRUS-1D is applicable tool and useful to assess deficit irrigation scenarios which is important for irrigation for irrigation planning to increase paddy rice productivity with climate change.

Appendices

Appendix 1: Documentation of AWD regimes and paddy rice experiments

i. Pot experiment set in glass greenhouse (phytotron) with sensors.

ii. Field monitoring and data collection during the experiment period

iii. Crop maturity stage and paddy rice harvesting

iv. Crop biomass harvesting and drying.

v. Counting the paddies and mature grains in Lab., Soil physics, TUAT, Japan.

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