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Water Management and Hydrological Characteristics of Rice-Paddy Catchments under AWD Irrigation Practice: Asia and Sub-Saharan Africa

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Abstract: Global concerns of decreasing water availability and food security are being exacerbated by the increasing demand for food, water quality degradation, and climate change impacts. Rice is an essential crop for food security with paddy rice cultivation largely practiced using traditional flooding conditions. Water regimes and components of the soil water balance in paddy rice catchments affect uptake of water by rice roots. Paddy management, especially puddling, significantly affects soil hydrological properties, such as hydraulic conductivity, percolation, and seepage in the paddy rhizosphere. Improved knowledge of these interactions is vital for developing sustainable water management strategies in paddy fields. Alternate Wetting and Drying (AWD) practice contributes to sustainable water management, but little is known about effects of soil wetting and drying duration on gravitational soil water flow, moisture dynamics, and hydraulic conductivity in the rice paddy rhizosphere. These factors depend on soil type, rice variety, rooting conditions, and environmental factors, such as solar radiation and temperature. Here we examine the paddy cultivation environment and soil properties under traditional continuous flooding and AWD practice. Some studies indicate that the duration and frequency of wetting and soil drying under AWD practice in paddy fields affects soil hydraulic conductivity that alters the next cycle of water application. During droughts and short rainy seasons, rainfall, soil properties, and atmospheric conditions control soil moisture dynamics in paddy fields. Limitations and challenges of applying AWD in paddy soils, including the variation of hydrological properties and the need for frequent field manual monitoring of water level (WL) head, are discussed. Implications of AWD practice on yield, water use efficiency, soil hydrology, and reduction of methane emissions, are outlined along with opportunities to improve AWD integration within government policies, irrigation schemes, and adoption by farmers. Coupled crop models can provide important insights for sustainable agricultural water management.

Keywords: water management; paddy soils; puddling; ecohydrological processes; climate change; preferential flow

1. Introduction

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 and food security [1,2]. 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 [3]. 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

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for food security [4,5], 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, irrigation supplies and costs may restrict paddy rice production, in some areas lending it unpracticable [6]. Likewise, extreme weather events, such as heavy rains attributed to climate change, cause huge damage and losses to paddy rice production. Similarly, changing rainfall patterns in African and Asian countries are prompting later paddy planting by farmers, thereby affecting rice yields [7].

Paddy production is declining and there is a concern that global warming may affect water availability and management for future paddy cultivation [8,9]. Increasing water shortages are affecting four billion people globally [10] and, by 2025, rice production is predicted to experience a 20% water deficit [11]. Although rice contributes significantly to ensuring global food security, traditional continuous flooding (CF) in paddy rice production requires more water than other cereal crops [12]. 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 [13]. Rice cultivation requires much water, up to 2500 L for 1 kg of rice produced, compared to other crops [14,223].

Therefore, it is critical to implement water management and agronomic strategies that reduce water use without affecting rice yields to support growing populations, with attention to minimal weed growth [223]. During drought conditions, appropriate irrigation management practices can lead to economic gains by maximizing rice productivity of applied water [15]. Several water-saving irrigation techniques have been developed recently for paddy rice cultivation. These include direct (dry) sowing, intermittent dry spells [16], partial root drying, alternating wetting, and drying irrigation (AWD) irrigation [17], and combination of shallow water depth with wetting and drying [18]. These irrigation and water management methods aim to improve water use efficiency. AWD is currently the most widely used water-saving technology in rice production [19]. A reduction of 10% in water use for irrigated rice would save 150,000 million m3, corresponding to about 25% of the total freshwater used globally for non-agricultural purposes [11]. Under AWD practice, paddy fields are subjected to alternate cycles of saturated and unsaturated conditions where water levels are allowed to subside until the soil reaches a specific moisture level, after which the field is re-flooded [14,15]. Furthermore, AWD has been reported to reduce water inputs by 23% compared to traditional, continuously flooded systems [20]. However, rice is more sensitive to drought stress, especially during the vegetative period compared to the flowering period [13].

From an agronomic perspective, even water application, as in the case of AWD, increases crop production and rice quality [20,21]. However, such water management strategies may mobilize Ni and Pb via Fe–Mn oxides, and by the formation of Pb ligands with carbonates and phosphates [22]; these may negatively affect microbial activities, such as carbon and nutrient cycling, in the rhizosphere. Such growth stage-related dynamics and the effect of metal uptake by crop roots depends on agronomic practices, and influence plant growth conditions [23]. Similarly, soil microorganisms are essential in producing and consuming carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4) in agricultural and terrestrial ecosystems. Microbes survive and gain energy by breaking carbon bonds in dissolved organic compounds [24]. This process becomes complete by electron transfer from the dissolved organic carbon (DOC) to electron acceptors. Atmospheric processes including carbon sequestration is required and important to reduce several Greenhouse Gases (GHG), particularly CO2, though the processes are complex [25].

Warming temperatures also affect rice growth patterns and emission of GHG. Agriculture is one of the main contributors of anthropogenic GHG emissions [Figure 1] and is expected to remain dominant in the 21st century [26]. Paddy rice cultivation and wetlands are a major source of global CH4 emissions, together contribute to about 41% of global CH4 emissions, although some estimates provide values as low as 12% [27]. Hydraulic conductance of roots varies with rice varieties and environmental conditions, which influences root anatomy and morphology under AWD practice [28]. However, hydraulic conductance of roots is one aspect that is largely overlooked in rice fields, including drought-induced reduction in hydraulic conductance due to xylem cavitation [29].

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Similarly, research on woody plants indicates an important hydraulic limitation on stomatal conductance and photosynthesis [30], a factor that could be equally important for herbaceous crops. Hydraulic conductance in rice roots can be lower than in other herbaceous roots. This low root conductivity, combined with a relatively high transpiration rate [31], explains the steeper drop in leaf water potential and leaf gas exchange in flooded rice environments.

AWD irrigation is practiced mostly in Asia employing triggering criteria for irrigation such as phreatic head or matric potential head [32]. For phreatic head, a perforated pipe (observation well) is installed at 15-20 cm below the soil surface and irrigation is applied when the water level in the tube disappears [17]. The matric potential head-based criterion involves applying water when the matric potential in the rootzone reaches between -20 kPa to -70 kPa measured by the tensiometers [32]. To understand AWD application criteria in detail, we review the state-of-knowledge on i) soil water interactions in paddy fields comparing traditional flooding and AWD irrigation as a climate smart technique, and ii) address questions related to:

a) The design and hydrological characteristics of paddy-rice catchments.
b) Whether puddling is essential in paddy rice catchments.
c) Suitable paddy soil conditions and the implications of intermittent soil wetting and drying on changes in hydrological properties, crop yields, irrigation efficiency, and GHG emissions in paddy rice catchments.
d) Reasons farmers are skeptical in adopting AWD practice.

Finally, the impact of AWD practice, limitations, and suitable soil conditions in paddy soils are discussed. Future research perspectives on improving AWD practice for adoption in Africa, primarily in the East Africa region, are also highlighted.

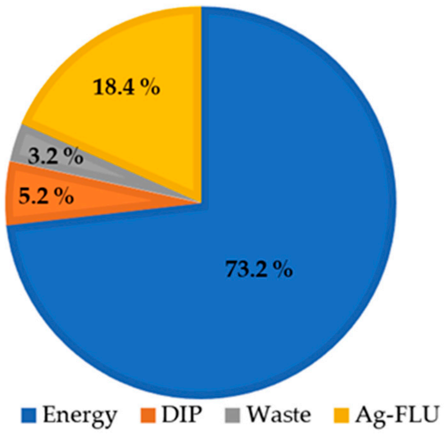

Figure 1. Global greenhouse gas emissions by major sectors. Where Energy includes electricity, heat, and transport, DIP; Direct industrial processes, Ag-FLU; Agriculture, Forestry and Land Use. Adapted from Ref. [222].

2. Attributes of Paddy-Rice Environment

2.1. Smallholder Agricultural Development in East Africa

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 [33]. 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. In addition, it involves intensive farmland consolidation to enhance regular fields in conjunction with straight segments of ditches and roads [34].

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 1). Irrigated lowland rice is

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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 [35]. 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 [35,36].

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 [37]. 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 [37]. 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 (Figure 2). Farmers control water within paddy fields during rice cultivation [38]. 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 [38]. 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 [39].

Table 1. Rice cultivation environment, climate, and major regions/countries.

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, southern 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

where RFS; Rainfed shallow, RFM; Rainfed medium, LGS; Long growing season, SGS; Short growing season, TW; Tidal wetlands.

2.2. 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 [40]. Water use efficiency is the ratio of dry crop biomass or grain yield produced to unit water transpired (used) by plants during cultivation [41]. 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 2). The water balance of lowland rice fields has been widely evaluated [42,43]. Similarly, the water balance of irrigation regimes influences the hydrologic relations of plant shoots which control crop root water uptake [2,44]. Previous research established that the hydraulic properties of roots of various crops have substantial co-regulation pathways that interact with root-soil systems [28,45,46]. 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 [47].

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A water balance helps to evaluate the efficiency of water usage in paddy fields and groundwater recharge [48]:

$$I+R=E+T+S+P+D+\Delta w \quad (1)$$

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:

$$v=IK \quad (2)$$

where: v, velocity of percolation; K, coefficient of permeability and I, hydraulic gradient [49]. The hydraulic gradient (I) is the change in hydraulic head per unit distance of travel in the soil layers.

$$I=H/L \quad (3)$$

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.

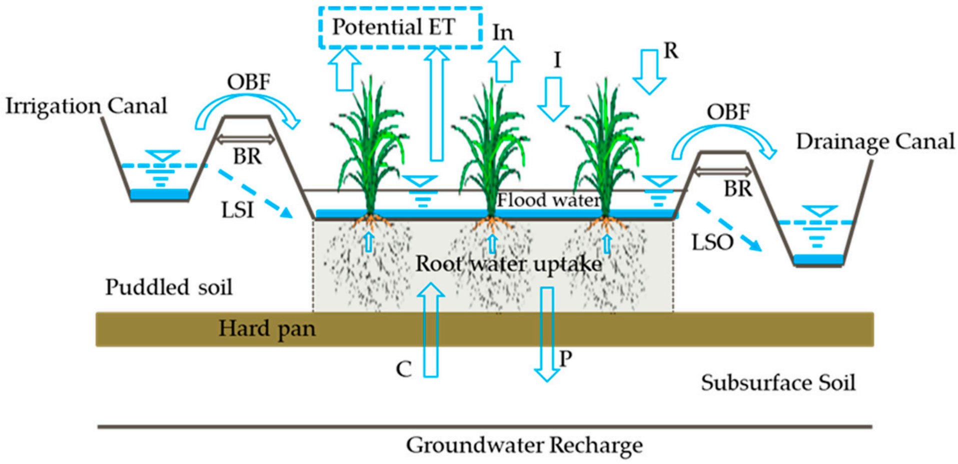

Figure 2. Schematic illustration of conceptual water balance and water flow in paddy field catchment. Where, C; capillary rise; Potential ET (evaporation, and transpiration), In; interception loss by canopy, I; irrigation, OBF; over-bund flow, P; percolation, R; rainfall, LSI; Lateral seepage inflow from irrigation canal, LSO; Lateral seepage outflow to drainage canal, BR; Bund/Ridge.

2.3. Hydrological Properties of Paddy Rice Catchments Under Traditional Flooding

2.3.1. Puddling, Bunds, and Preferential Flow

Paddy field preparation is vital for creating favorable conditions for rice cultivation [50]. This includes puddling, a labor and capital-intensive activity where soil is ploughed and harrowed repeatedly during submerged conditions. Puddling facilitates transplanting and reduces percolation loss of water and nutrients [51]. However, it creates physical soil conditions detrimental for upland crops in rice-based cropping systems [52]. A typical soil profile of a paddy rice field consists of three distinct layers: top puddled layer, the middle-consolidated layer (also called the hard pan), and the bottom undisturbed soil [53]. The puddling index (PI) of soils in paddy rice fields depends on farmers' tools, which include mechanical/tractor puddling implements such as cultivators, disc harrows, rotovators, and confine wheels. PI can be estimated using the formula [50–54].

$$PI = \frac{V_s}{V_t} \times 100 \quad (4)$$

where: PI, puddling index (%); Vs, settled/suspended soil volume in the measuring cylinder after 48 h (ml); and Vt, total volume of sample collected (ml).

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It is logical to question whether puddling is essential in paddy fields and, if yes, in what conditions. The benefits of puddling in paddy fields have been reported [51,52] and include: i) increased water holding capacity and yield due to increased soil microporosity, but most importantly, decreases in macroporosity; ii) reduced air-filled pore volume by replacing it with water; and iii) ease of transplanting, nutrient availability, and weed control. Also, disadvantages associated with puddling in paddy fields have been highlighted: firstly, the presence of a hardpan (compacted layer) and development of a low hydraulic conductivity layer after puddling that resists root penetration. The degree of soil compaction depends on soil type, cultivation practices, wetting and drying cycles, temperature, and years of crop production. Secondly, puddling destroys soil aggregates, breaks capillary pores, and disperses fine clay particles, lowering soil strength in the puddled layer and causing waterlogging. Thirdly, it increases field water use and crop water requirements [52].

Additionally, characteristics of the hardpan are high bulk density and low saturated hydraulic conductivity (Ks) since the layer within the hardpan is usually more impervious to water than the overlying soil layers [55]. Hydraulic properties of hardpan dominantly control the water regime of puddled paddy fields often creating an unsaturated zone below the hardpan [53,56]. Two other features of rice fields that affect their hydrology are: 1) the bund of raised soils surrounding the field that retains irrigation water; and 2) cracks that form preferential flow channels. Preferential flow in the vadose zone travels through localized pathways (macropores) bypassing the surrounding soil matrix and sometimes accounting for most of the flow in soils [57,58]. The hardpan formed while working paddies in saturated conditions, thus compacting the soil, and destroying aggregates, acts as a barrier to water flow. Excavating through the hardpan can significantly increase water loss from the field [48,53]. Smaller soil particles fill pore space and seal cracks and macropores as they deposit [52]. The difference in effective hydraulic conductivity between the hardpan and subsoil facilitates the development of an unsaturated zone directly underneath the pan, even while the field surface is flooded [48–59].

2.3.2. Percolation and Seepage

While percolation is the vertical movement of water below the root zone to the water table, lateral seepage is the movement of subsurface water from one paddy field to another (Figure 2). Percolation and lateral seepage represent the primary water losses from lowland paddy rice fields [56,59,63]. Water percolation infiltrates the hardpan and progresses deeply, contributing to recharging of aquifers and can be reused for irrigation (Figure 2). Percolation rate after puddling depends on the soil redox potential and water management [61]. In contrast, seepage moves laterally by pressure head differences between fields, thus decreasing the amount of water recharged into the aquifer (Figure 2). Therefore, lateral seepage must be separated from infiltration to estimate effective groundwater recharge from rice paddies [53,56,59].

Water flow through soils is controlled by several factors, including relatively static soil structure and composition. In actual field practice, percolation and seepage are inextricable. Percolation rates in puddled rice fields are influenced by several factors such as soil structure, texture, puddling method and frequency, bulk density, organic matter content, mineralogy, and concentration of salts in soil solution [64]. Generally, heavy textures (e.g., montmorillonite clay), high sodium levels in irrigation water, and high bulk densities favor effective puddling and low percolation rates [53,56,59]. Additionally, these dynamic processes are influenced by soil physical and hydraulic properties and water regimes [55]. Increased ponded water depths increase percolation due to the larger hydraulic gradient imposed [64]. Paddy rice is a semi-aquatic plant, and percolation influences rice yields [63]. Rice cultivation is recommended in soils with minimum percolation rates (mm/day), defined as: Excellent, 1-2.5; Good, 2.5-5.0; Marginal, 5.0-10.0 and Unsuitable > 10.0 mm/day [65]. The effect of puddling on soil bulk density, hydraulic conductivity and percolation with different methods and tools is shown in Tables 2 and 3.

Table 2. Effect of puddling on soil bulk density with different puddling methods/tools. Source: [54].

Treatment	Descriptions	Bulk density, g/cc	
		Bulk density	After Puddling
T1	Cp	1.492	1.333
T2	CP+HBP	1.492	1.193
T3	Cp+W+HBP	1.542	1.247
T4	VP+HBP	1.425	1.305
T5	VP+W+HBP	1.425	1.322
T6	CP+HBP+SFR	1.500	1.300
T7	CP+W+HBP+SFR	1.517	1.283
T8	CP+W+HBP+W+SFR	1.385	1.252
T9	CP+HBP+W+SFR	1.450	1.255
T10	VP+HBP+W+SFR	1.433	1.330
T11	VP+W+HBP+SPR	1.442	1.277
T12	VP+W+HBP+W+SFR	1.433	1.383
T13	VP+HBP+W+SFR	1.492	1.217

where Cp; Country plough, HBP; Helical bladed puddler, SFR; Sheep foot roller, W; Water (24 h), VP; Victory plough.

Table 3. Comparative effect of different puddling tools on percentage (%) reduction of hydraulic conductivity and percolation loss. Adopted from Ref. [54].

Treatment	Puddler Type for treatment description	Hydraulic Conductivity		Percolation Loss	
		Total cm/hr	% reduction over control	Total cm	% reduction over control
T_1	Disc harrow	0.052	74.44	111.7	25.56
T_2	Angular bladed puddler	0.031	84.87	066.1	15.13
T_3	Deshi plough	0.098	51.40	212.3	48.60
T_4	Moldboard plough	0.075	63.17	160.9	36.83
T_5	Control (No puddling)	0.203	-	436.9	-

2.4. Paddy Rice Cultivation and Crop 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 4). 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 [39]. 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" [39]. 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 [15]. The daily paddy-rice water consumption varies from 6 to 10 mm/day depending on agro-climatic conditions during crop cultivation [15]. Irrigation planning and design decrease crop water requirements in paddy fields;

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the planned water requirement rate is at 10–20 mm/day, although actual water requirement rate may reach 20–30 mm/day [66,67] 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 [68,69]. 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 $CO2$ (gas) and photosynthetic metabolic potential [70].

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 [71]. 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 [72]. 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 [73]. 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 [74].

Table 4. Crop water requirement of each stage for rice paddy. Adapted from Ref. [202].

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

2.5. Water Management Strategies in Paddy Rice Watershed.

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 [35]. 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 [75].

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-

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transplanting of single seedlings, transplanting in the square, irrigation management, weed control, and fertilizer application [76]. SRI techniques are based on close field observations of the biological characteristics of rice plants while manipulating the natural genetic potential [77]. 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 [76,78].

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 [78]. Rice production is strongly affected by water availability and yield increase is a function of increases in transpiration and reduction in other water balance factors, i.e., evaporation, seepage, and percolation [79,80]. 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 [35,81].

Similarly, water-saving techniques are essential to help farmers cope with water scarcity due to climate change [82]; these include: i) direct seeding; ii) saturated soil culture; and iii) Alternate Wetting and Drying practice [81]. 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 [83]. 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 [84] was not effective in reducing the total amount of water used or increasing crop productivity. Classifications of directly seeded rice system is shown in Table 5.

Table 5. Classification of directly seeded rice systems. Adapted from Ref. [83,203].

Direct Seeding Systems	Seed Condition	Seedbed condition and environment	Seeding pattern	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 [35]. 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 [20].

2.6. Climate Change and Paddy Cultivation

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 [85,86]. Climate is denoted by either climate variability or climate change, i.e., short-term, or long-term variations ranging from decades to millennia [87]. Although agriculture is likely the most vulnerable sector to climate change because of potential impacts on food production, climate effects are not evenly distributed [88]. Developing regions such as Africa are severely affected by climate change due to low adaptive capacities and slow recovery trajectories [89,90]. The impacts of climate change on rice production have been studied at regional and global scales [92–94].

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 [90,94,95]. Climate variability in most parts of Africa occurs on seasonal and decadal time scales and the region experiences frequent droughts and floods [87,94]. As a result, these climate threats are major causes of hunger, malnutrition, poverty, and obstacles to social and economic development [94].

Rice is a staple food for more than 3 billion people globally, and consumptive demand has surpassed the production rate since 2000 [96]. By 2010, rice production was 696 million tons, with 90% [Table 6] coming from Asia [97]. Conversely, rice production is equally a contributor to and a target of climate change. Climate events such as droughts, floods, saltwater incursion, and extreme temperatures globally destroy crops, jeopardizing more than 144 million smallholder rice farmers every growing season, with a large percentage of smallholder farmers in SSA [94,98]. Such damaging events are projected to exacerbate rice production value chains in the future [98], thus threatening global rice value chains, particularly in Africa. Furthermore, little research focus has been given to explore the effects of climatic variations and patterns along the rice production value chain at the sub-regional scale in SSA [99].

Studies on climate trends and drought indices, in the Mun River basin, Thailand, revealed declining rice yields to the lowest levels in Asia [100]. These declines in rainfed rice yield were attributed to water shortages. Additionally, 90% of rice cultivation in the Mun River basin is affected by climate variability and change [100]. Vietnam is one of the leading rice-producing regions and the world's largest exporter of rice, growing 90% of exported rice in the Mekong River Delta [101,102]. Rice production in this region has declined due to low-lying topography, which is vulnerable to sea level rise, saltwater intrusion, and storm surges [103]. Likewise, rising temperatures may detrimentally impact rice production in the region, which contributes 65% of farm income [104].

Similar evidence of negative climate impacts on rice production, based on observations or projections, are noted in SSA. Reductions in rice yields have been reported in Tanzania, Burkina Faso, West Africa, and across SSA [98, 105-107). Reduction in both rice yield and grain quality were found in Nigeria, declining crop productivity in South Africa, and substantial crop and income losses occurred among smallholder farmers in Madagascar [109,110]. These responses are attributed to negative climate impacts that differ from regions to countries with time. In Kenya, changes in temperature have a greater impact on rice production than changes in rainfall because irrigated rice production dominates [111].

Studies indicate that global warming will have considerable impacts on crop productivity and quality [112–114]. Research in Japan shows that high temperatures during the growing period drastically degrade rice grain quality [114]. Degradation of rice grain quality is a serious issue in Japanese rice production, which will likely cause large economic losses [115]. Therefore, strengthening climate adaptation and mitigation measures should be emphasized and immediately implemented to improve rice yields and reduce GHG emissions from paddy fields.

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Table 6. Top 15 rice producing countries in the world (Milled production, 1000 metric tons) for the past 5 years. Adapted from Ref. [204].

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

2.7. Integrated Paddy Rice-Fish Culture

Agricultural production in rural areas faces many challenges that differ amongst regions, such as aging farmers, low motivation for agriculture work among youth, limited agricultural land, and the unpromising sustainability of conventional rice production making it less attractive as an agrobusiness in various communities [116]. This widens the gap between rural and urban development in several developing countries and has contributed to population increase in cities while the poverty rates in rural areas remain high [117]. Likewise, integrated irrigation in paddy fields and aquaculture plays important roles in ensuring food security, national economic growth, and poverty reduction [118]. Recently, rice-fish culture has been reported in several SSA countries, and although precise figures on integrated production are scare, Madagascar is the leader with approximately 70% of their freshwater fish production based on integrated rice-fish culture [119,120]. Rice-fish culture promotes integrated water use within paddy fields and enhances linkages between water management and aquatic ecosystems [121]. However, massive hydraulic engineering works associated with large-scale irrigation development can negatively impact river ecosystems, leading to loss of biodiversity [122]. Attempts to develop irrigation systems that abate this impact by promoting integrated rice-fish culture have not been adequately explored [123].

Innovative approaches such as rice-fish culture are appropriate technologies to boost rice productivity in paddy fields. Integrated rice-fish culture is global heritage system and has been widely practiced for about 2000 years in Southeast Asia, including parts of China and Indonesia, although it is comparatively new in SSA [124–126]. Rice-fish culture is applicable to production of tilapia, carp, ornamental fish, catfish, and giant prawns [116] and can be coupled with technically designed irrigated rice fields.

Rice-fish culture has been widely practiced in wetlands and floodplains where rice paddies and inland fisheries exist. For example, in West Africa, farmers keep wild fish in rice paddies during the dry season [127,128]. Total rice-fish farming land potential in Indonesia is about 8.1 million ha, with irrigated land and non-irrigated land comprising 39% and 61% of the areas, respectively [116]. Rice-fish farming business benefits farmers in southern Thailand by maximizing paddy field resources [129]. Integrated rice-fish culture is effective in reducing applications of pesticides and chemical fertilizers, while boosting farm productivity and income [130]. Rice-fish culture practices vary based on biophysical and technical aspects, such as the use of natural or stocked fingerlings, water control measures, fingerling density, and volume of production inputs [131,132]. Rice-fish culture has been practiced in Cambodia due to consequences of socio-political crises, and recent government policy interventions recognize the importance of this as a productive fishery, contribution of food security and nutrition, and cultural indebtedness of wild sourced foods [133]. Rice-fish culture occupies 2.6 million ha in wet season rice landscapes of Cambodia because of little irrigation (17% of total area) and expansive rainfed lowlands [133].

To utilize the paddy field ecosystem services for societal benefit, better understanding of biodiversity components such as phytoplankton, zooplankton, macroinvertebrates, fish, mammals, and birds, including structure and function of species diversity within the integrated food web is vital [134]. Interaction exists among these factors, for example, rice and phytoplankton control water quality through reduction of nitrogen and phosphorous, while zoobenthos facilitate energy flow in the entire ecosystem [135,136]. However, limited research has been conducted on the interrelationships among these factors in paddy ecosystems supporting rice-fish culture. Thus, the adoption of this technology by farmers depends on not only the available resources, but also on social conformity.

3. Defining AWD Practice in Paddy-Rice Catchments

In AWD, rice paddies are intermittently irrigated, except during the rooting, panicle formation, and flowering stages, reducing water use by 15-40% [137]. 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 (Figure 3) [17]. 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 [32,35].

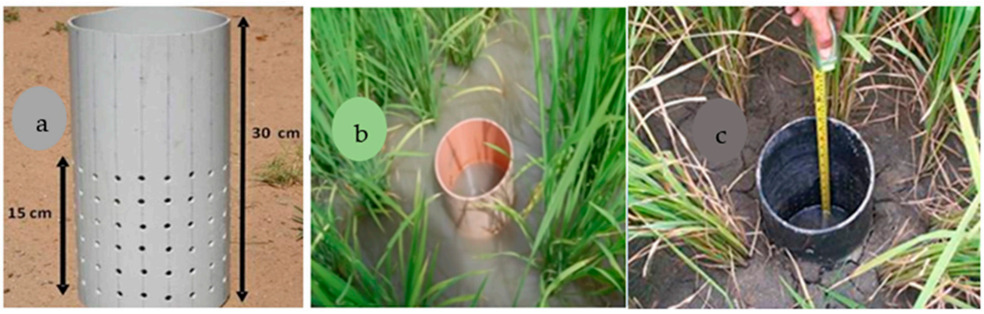

Figure 3. Practical application of AWD practice: a) field observation PVC water tube; b) flooding condition, and c) soil drying and water depth measurements using a meter ruler. Adapted from Ref. [82,137,139].

3.1. AWD Recommendations

The most practical approach of AWD irrigation by farmers in the paddy field is using a field water tube ('observation pipe') [137]. The perforated observation tube has holes (0.5 cm diameter) drilled at 2 cm apart throughout the buried length of the tube (Figure 3). 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 [138]. 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) [139]. 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 [137,139] 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 [82]. Fertilizer application, particularly nitrogen, is recommended on dry soil before irrigation, similar to traditional flooding [139]. 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 [139]. Siltation is a problem due to clogging of perforations and has been reported to reduce the performance of AWD using observation water tubes [22]. 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 [140]. 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 [141]. 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 [139].

3.2. Impacts of AWD Irrigation Practice

3.2.1. Crop Height, Yield, and Yield Components

Rice is sensitive to any water stress and unsaturated soil conditions [13]. 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 [14]. Any decrease in irrigation regimes tends to induce drought stress, contributing to a decline in net photosynthesis and reduced growth through the inhibition of cell elongation or cell division [142]. 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) [13].

Furthermore, if water declines to 15 cm in observation tubes, the soil is still near saturation and water is available for rice growth [Figure 4] 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 [143]. 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 [20]. 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 [14]. These differences can be due to the high percentage of exchangeable sodium (Na) which causes dispersion in alkaline soils [144]. 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 [145].

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Additionally, high levels of Na 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 [144]. When AWD is practiced throughout the season, yield reductions were observed compared to when practiced in either the vegetative or reproductive stages [14].

Not all the rice crop tillers develop to mature tillers; some become dormant when young and die later depending on environmental and nutritional conditions [146], 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 [147]. In contrast, short-duration soil drying does not affect crop growth, rice tillering, and general yields [13].

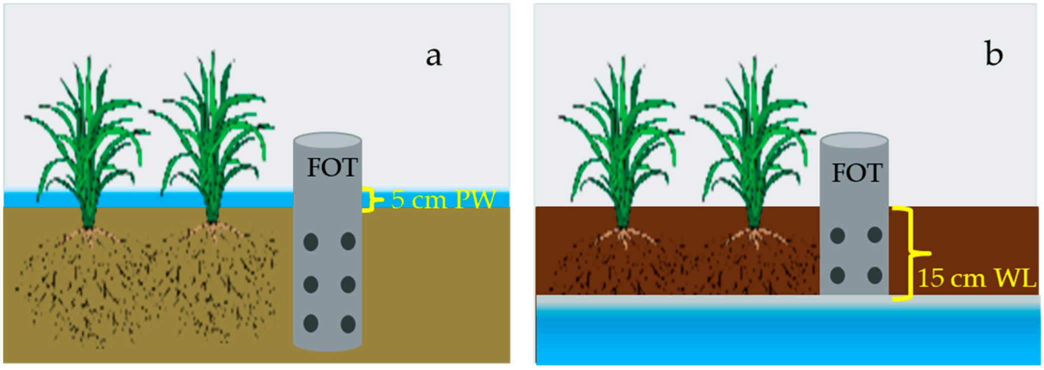

Figure 4. Illustration of AWD conditions: a) soil wetting during irrigation; b) soil drying after given days; FOT-field observation tube or well, WL-water level/water table below soil surface, PW-ponded water after irrigation. When WL is allowed to drop ≤ 15 cm depth is considered safe AWD condition.

3.3.2. 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 [148,149], India [150] and The Philippines [151], 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 [14]. 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 [152]. Nevertheless, AWD technology significantly reduces irrigation frequency compared to typical rice paddy practices, lowering irrigation water consumption by 25%, as well as fuel (30 L/ha, during one growing season) [153]. The effect of AWD practice on yield and water productivity is summarized in Table 7.

Table 7. Summary of impacts AWD irrigation practice on paddy rice yields, water saving and water productivity.

S/N	Component	Details	Authors
		Higher Wp (1.74 g L^{-1}) in AWD compared to CF (1.23 g L^{-1})	[205]
		WUE (85.55 (kg ha^{-1} cm) in AWD with quite a large water saving (15 cm) compared to continuous submergence	[206]
		Water saving of 15–20% with AWD without a significant impact on yield	[148]

		A 26.34 % reduction in water use and only a 6.40% reduction in grain yield compared to the CF. Observed up to 36 % water saving in AWD conditions	[13,223]
1	Wp, WUE, Water Saving	Water application once in 7 days consumed the lowest amount of water (80.30 cm) and saved 41% water	[207]
		Water savings in AWD by 40–70%, 20–50% compared to CF	[208]
		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})	[138]
		AWD improves WUE and yields with 5, 7 and 10 days of irrigation interval	[140,209]
		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	[138,210]
		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	[211]
		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	[212]
2	Yield components	Water application intervals of 5 and 8 days with CF produced statically the same grain yield. (7342, 7079 and 7159 kg ha^{-1}, respectively)	[213]
		Grain yield was higher in saturated condition (7.6 t ha^{-1}) compared to CF (7.1 t ha^{-1}) in Malaysia	[214]
		Application of safe AWD levels did not result in loss of rice yield	[215]
		Increases rice yield by 10% with AWD	[180]

Where Wp; Water productivity, WUE; Water use efficiency, CF; Continuous flooding method.

3.2.3. Paddy Soil Hydrological Properties with AWD Practice

Paddy soils generally have high clay content, water holding capacity, and nutrients [154]. Paddy soil typically consists of at least 35% clay, thus, clay-textured according to USDA [155]. Formation of cracks in heavy clay soils affects agricultural water and crop production, a characteristic feature of paddy soils with AWD practice [156]. Alternatively, swelling and shrinkage in paddy soils are driven by decreased soil moisture and clay content that differ spatially [154,157]. 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 [58,156]. These cracks are less conspicuous with continuous flooding [158,159]. 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 [160]. The amount and extent of crack occurrence controls the preferential routing of water losses via percolation and seepage [161]. Therefore, cracks significantly affect the accuracy of the field measurement of ponded water after irrigation.

Cracks create preferential flow pathways, facilitating water infiltration [162] and increase the risk of groundwater pollution via fertilizer, pesticide, and herbicide percolation [163]. These pathways allow water to bypass the soil matrix [164]. Evidence from field research indicates that 70–

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85% of water flux may be attributed to preferential flow. This creates challenges for predicting water and solute movement in field conditions [165–167]. Cracks formed during soil drying increase hydraulic conductivity; during wetting, crack closure reduces the infiltration rate [162]. 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.

3.3.4. Redox Potential with AWD Practice

Although water savings are achieved with AWD practice, savings can be improved by modifying the rooting behavior of rice cultivars [168]. AWD has potential to alter macro and micronutrient availability and uptake. Aerobic growth favors enhanced selenium accumulation in rice [169], while decreasing arsenic uptake [170,171]. 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 [172].

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 [168]. Additionally, redox potential is challenging factor with water regimes, although high redox potential with AWD practice can be evident between booting to grain formation in rice paddy [223]. Soil redox potential (Eh) influences net $NH4+$ (de) fixation, which refers to both fixation and de-fixation of $NH4$ in paddy soils through nitrogen (N) fertilizer application. All structural $Fe3+$ in phyllosilicates is biogenically reduced with a consequent increase in the negative charge of clay minerals, which creates strong action between $NH4$ cations and clay minerals at low Eh [173,174]. The effect of Eh on $NH4+$ (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 $NH4+$ concentrations and dynamic balance with fixed $NH4$ [175].

4. Adoption, Potential Challenges and Limitations of AWD Practice

Policies for promoting and disseminating AWD were introduced in several Asian countries due to its benefits. 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 [176]. 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.

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 [177]. 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 systems 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 [168,178]. Cadmium (Cd) accumulation in grains is debatable for paddy rice grown in more aerobic conditions [179]. However, some research has shown that mild and severe paddy soil drying can reduce grain accumulation of Cd [180]. Therefore, in promoting and adopting AWD programs, reducing Cd accumulation in rice grains should be prioritized [181].

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

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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 SSA, should develop workable policies that enhance adopting such appropriate technologies given changing climatic conditions affecting paddy rice farming.

4.1. AWD Practice as Climate Adaptation and Mitigation Strategy

The efforts to increase water productivity, climate adaptation, and mitigation in paddy production systems is part of the growing subject on climate-smart agriculture (CSA). Specific indicators focused on those efforts in line with governmental plans and policies on adoption of agricultural water management practices (including AWD), are necessary to support the concept of CSA. Therefore, evaluating the relative climate 'smartness' of these water management techniques require metrics that concurrently amalgamate all the three points (productivity, adaptation and mitigation) while comparing various water management strategies and offering different benefits, trade-offs or synergies from the three points [182].

However, water resources and irrigation development for paddy rice production require a significant transformation, especially in developing countries, to meet food security challenges and climate change. Recently, increased human activities have influenced global climate where water and GHG emissions are two key factors affecting climate [153]. Besides, AWD technology has been proven as a GHG mitigation measure, particularly reducing CH4 emissions up to 50 %. CH4 is produced anaerobically by methanogenic bacteria that thrive in paddy rice fields (Figure 5). Hence, traditional flooding in paddy rice catchments is the largest source of CH4 emissions, the second largest anthropogenic source after ruminant livestock [153]. Previous studies indicate that AWD technology can reduce CH4 production up to 60% [183].

In contrast, AWD influences the production of nitrous oxide (N2O), another potent GHG gas. The N2O 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 CO2, while CH4 has a GWP of 25 [184]. N2O 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 N2O emissions under different water management regimes are scarce [153].

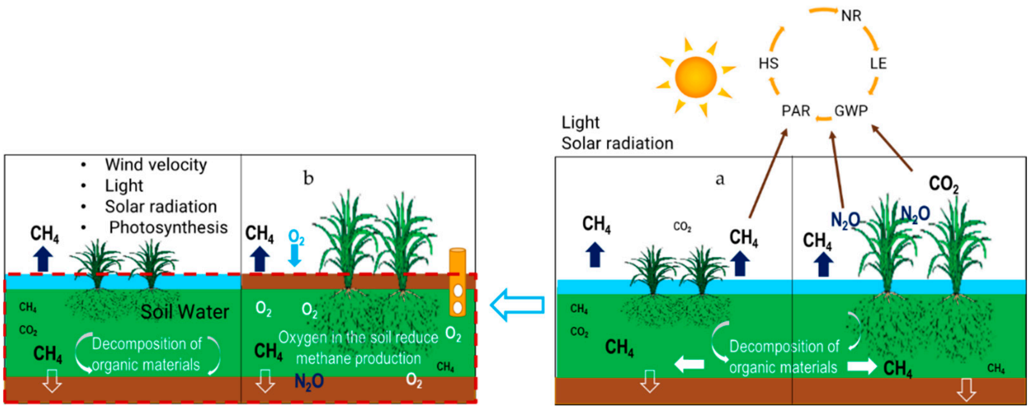

Figure 5. Conceptual illustration of changes in SOC and GHG interactions in paddy field under; a) Anaerobic respiration in absence of oxygen under traditional flooding conditions (CF), and b) Aerobic respiration in presence of oxygen due to soil drying conditions under AWD Irrigation. Where GWP; Global Warming Potential, PAR; Photosynthetically active radiation, HS; Sensible Heat, NR; Net Radiation; LE, Latent heat.

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4.2. Methane GHG and Carbon Equivalent Estimation in Paddy Rice Catchment

There are several approaches for estimation of GHG emissions including methane in paddy fields. However CH4 emissions from paddy fields can be estimated as follows [185]:

$$CH_4Rice = A \times t \times EF_i \times 10^{-6} \quad (5)$$

where: CH4Rice = Amount of CH4 emissions from rice cultivation (Gg CH4 yr-1)
A = Annual harvested area (ha yr-1) or (m2/yr)
t = Cultivation period of rice (day)
EFi = Emission factor for harvested area (kg CH4 /ha/ day)

The seasonally integrated emission factor is evaluated from direct field measurements of methane fluxes for a single crop. In field practice, it is necessary to calculate the total annual emissions for a country as a sum of the emissions due to several conditions. Total rice production is divided into subcategories based on different biological, chemical, and physical factors that control methane emissions from rice fields. For large countries, this may include different geographic regions. To account for the different conditions, Fc is defined as the sum of EFi (Eqn. 6). This approach to emissions estimation can be represented as follows:

$$F_c = \sum_i \sum_j \sum_k E.F._{ijk} \times 10^{-12} \quad (6)$$

where, i, j, and k are categories under which methane emissions from rice fields may vary. For example, i may represent water levels in the rice fields, such as fields inundated for the duration of the growing season (flooded regime) or fields under water with AWD practice conditions. This occurs either under managed irrigation when water is not readily available or when rains do not maintain flooded conditions throughout the growing season (intermittent regime). Subscripts j and k may represent water regimes modified by other factors like organic inputs, soil texture, fertilization regimes for each condition represented by index i. When more factors are identified, more categories need to be included. The additional parameters should lead to an improvement in the estimate of the total emissions. The summation should include all cropping seasons.

The GHG emission to carbon dioxide equivalent can be estimated from the equation:

$$CO_2e = GHG \times GWP \quad (7)$$

where:
CO_2e = Equivalent Carbon dioxide
GHG = Greenhouse gas
GWP = Global warming potential (Metric ton)

4.3. Water Management and Carbon Dynamics with AWD in Paddy Rice Fields

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 [186]. Soil organic matter is crucial for both plant and CH4 productivity [Figure 4] 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) [187]. 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 [188]. 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 [189]. Likewise, a comprehensive accounting is needed to place GHG reduction and carbon dynamics in a broader context thus balancing reduction in CH4 emissions with increase in CO2 production [186].

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5. Suggestions and Future Research Perspectives

Decreasing water availability for irrigated agriculture due to climate change is threatening paddy rice production. 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.

Our synthesis from studies and practice suggests that the application of the AWD technology is either conducted by WL or moisture status (SWP). Additionally, the general classification of AWD based on SWP exceeds the defined recommendations by IRRI prompting further research and redefining AWD depending on soil type and structure. While the application of AWD using SWP in the rice rhizosphere gives valid values that indicate the ability of rice roots to absorb water from the soil matrix, it is difficult for farmers to implement AWD with SWP due to the cost of sensors and devices, as well as the required technical knowledge. Applying AWD by measuring the declining water table in the field (WL) using observation tubes is widely accepted. The corresponding SWP may not match the WL and the efficiency of WL measurement is affected by soil type, variations in paddy field slopes, and spatial variation of hydraulic conductivity with depth in paddy fields. Likewise, automation of AWD practice using smart sensors based on internet of things (IoT) could improve water use efficiency based on real-time alerts applying information on soils, crops, and weather [190]. IoT is an emerging concept that deals with connections of physical and digital items.

AWD practice influences hydrological properties in paddy rice catchments. Assessing climate suitability of AWD combined with research on changes of hydrological properties of paddy catchments will improve water management and adoption in several parts of the world. Therefore, seasonal mapping of paddy catchments at sub-regional, national, and local paddy rice field scales using GIS and remote sensing can provide appropriate information on the suitability for AWD adoption. Research on climate suitability analysis and potential of AWD practice was assessed in Cagayan province, The Philippines, and Burkina Faso, SSA. These evaluations were based on soil water balance models (SWB) and remotely sensed data to assess the viability of AWD as a climate mitigation option. SWB models rely on readily available and easily derived spatial and statistical data for rice areas, rice seasons, rainfall, potential evapotranspiration, soil texture, and percolation rates in paddy rice catchments [191]. The climate suitability for AWD from the Philippines for the dry season was highly reliable as expected for dry season rice systems that rely on irrigation. Considerable rice areas were deemed climatically suitable for AWD during the wet season, contrary to the perception that AWD is not suitable in rainy seasons because excessive rainfall prevents drainage [191]. Similar research on the potential for expansion of irrigated rice under AWD in Burkina Faso shows that the entire dry season was suitable for AWD implementation compared to 25–100% of the wet season. Additionally, soil percolation is the driver of the variation in irrigated land suitable for AWD in the wet season [192].

Detailed modelling of soil water dynamics of AWD regimes for different paddy soils is important to understand the implications of soil wetting and drying on the paddy rhizosphere and ecohydrological properties such as evaporation, transpiration, puddling, water flow, and nutrient transport in paddy rice catchments. Numerical models are helpful in determining the optimal WL in water pipes or SWP and deciding the irrigation triggering conditions in AWD without performing field experiments. These numerical models, including FEMWATER, SAWAH, SWAP, SWAT, and HYDRUS, have been adopted to simulate soil-water dynamics in paddy conditions in one, two, or three dimensions, basing on hydrological characteristics. While the 1-D SAWAH model cannot simulate both horizontal and vertical water movements, a 3-D FEMWATER finite element model was developed to differentiate vertical percolation and lateral seepage from surface infiltration for varying wet and dry conditions [193]. Similarly, HYDRUS is a comprehensive model that simulates soil water flow of AWD regimes due to changes in wet and dry conditions in 1-D, 2-D, or 3D [194]. HYDRUS-1D has been applied to simulate water flow, water balance components, and ponding in paddy soils under AWD practice while accounting for groundwater capillary rise during the wet season [32,195].

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Long term evaluation of drought (water) stress index in rice fields and its effect on the yields, soils, and root architecture of different paddy rice cultivars is vital. Crop water stress index (CWSI) is a classic index developed for wet or dry surfaces to capture progressive water stress of different crops. Additionally, evaluation of CWSI using an infrared thermometer to measure canopy temperature enhances precision irrigation water management, enabling continuous monitoring of crop water status by integrating both soil water status and climatic conditions. This application is non-destructive, scalable from plant to field conditions, less laborious, and implemented at larger spatial or temporal scales compared to other techniques, such as soil moisture sensors [196–199].

Additionally, improving integrated climate and rice crop (Oryza sativa) models through coupled modeling for paddy rice catchments is necessary since rice feeds more people compared to other crops [36]. Agricultural water uses and management relies on various factors, such as climatic conditions, topography, lithology, soil, management practices, and crop type. Coupling hydrologic and crop models is becoming increasingly important for sustainable water management, irrigation systems, and alleviating challenges related to data availability. Research on coupling hydrologic and crop models is relatively scarce and is still at an early stage of development [216]. Modelling studies have shown varying results on rice response to future climate change. Whereas increased night temperatures are correlated with declining rice yields [8], several model results suggest that CO2 'fertilization', i.e., increasing atmospheric CO2 levels that improve crop productivity, may offset yield losses from increasing temperatures [217–220].

Finally, designing an integrated approach for adoption and promotion of AWD technology to improve on water management, especially in East Africa, requires: 1) increased 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 [221]. 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 [153].

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References

1. Misr, K.A. Climate change and challenges of water and food security. Intl. J. Sust. Built Environ. 2014, 3, 153-165.
2. Sidle, R.C.; Khan, A.A.; Caiserman, A.; Qadamov,A; Khojazoda, Z. Food security in high mountains of Central Asia: a broader perspective. BioSci. 2023, 0, 1–17.
3. Parthasarathi, T.; Vanitha, K; Lakshamanakumar, P; Kalaiyarasi,D. Aerobic rice-mitigating water stress for the future climate change. Intl. J. Agron. Plant. Prod. 2012, 3 (7) 241-254.
4. Djaman, K.; Mel,V; Boye, A.; Diop, L.; Manneh, B.; El-Namaky, R.; Futakuchi, K. Rice genotype and fertilizer management for improving rice productivity under saline soil conditions. Paddy Water Environ. 2020, 18, 43–57.

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5. Pourgholam-Amiji, M.; Liaghat, A.; Ghameshlou, A; Khoshravesh, M; Waqas, M.M. Investigation of the yield and yield components of rice in shallow water table and saline. Big Data in Agriculture (BDA). 2020, 2 , 36-40.
6. Delong, M.; Wieland, F. Changes in root hydraulic conductivity facilitate the overall hydraulic response of rice (Oryza sativa L.) cultivars to salt and osmotic stress. Plant Physiol. Biochem. 2017, 113, 64-77.
7. United Nations, Variable rains and flooding impact on rice harvest. https://www.thenewhumanitarian.org/news/2008/04/01-1, 2008 (Accessed 20 April 2023).
8. Peng, S.; Huang, J; Sheehy, J.E.; Laza, R.C.; Visperas, R.M.; Zhong, X.; Centeno S.G.; Khush, S.G.; Cassman, G. Rice yields decline with higher night temperature from global warming. Agric. Sci. 2004, 101 (27), 9971-9975.
9. Saud, S.; Wang, D.; Fahad, S.; Alharby, H.F.; Bamagoos, A.A.; Mjrashi, A.; Alabdallah, N.M.; AlZahrani, S.S.; AbdElgawad, H.; Adnan, M.; Sayyed, R.Z.; Ali, S.; Hassan, S. Comprehensive Impacts of Climate Change on Rice Production and Adaptive Strategies in China. Front Microbiol. 2022, 13, 926059.
10. Mekonnen, M.M.; Hoekstra, A.Y. Four billion people facing severe water scarcity. Sci. Adv. 2016, 2, e1500323–e1500323.
11. Tuong, T.P.; Bouman, B.A. Rice production in water–scarce environments, In: Kijne JW, Barker R, Molden D (eds), Water productivity in agriculture: limits and opportunities for improvement. CABI Publishing, Wallingford, UK, 2003; pp. 53–67.
12. Pimentel, D.; Berger, B.; Filiberto, D.; Newton, M.; Wolfe, B.; Karabinakis, E.; Clark, S.; Poon, E.; Abbett, E.; Nandagopal, S. Water resources: agricultural and environmental issues. Bioscience 2004, 54 (10) 909–918.
13. Bwire, D.; Saito, H.; Mugisha, M.; Nabunya, V. Water Productivity and Harvest Index Response of Paddy Rice with Alternate Wetting and Drying Practice for Adaptation to Climate Change. Water, 2022, 14(21), 3368.
14. Carrijo, R.D.; Lundy, E.M.; Linquist, A.B. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Res. 2017, 203, 173–180.
15. Mote, K.; Rao, V.P.; Ramulu, V.; Kumar, K.M.; Uma Devi, M. Performance of rice (Oryza sativa (L.)) under AWD irrigation practice-A brief review. Pad. Water Environ.2022, 20, 1–21.
16. Feng, Y. Exploring options to grow rice using less water in northern China using a modelling approach I: field experiments and model evaluation, Agric. Water Manage. 2007, 88, 1–13.
17. Lampayan, R.M.; Samoy-Pascual, K.C.; Sibayan, E.B.; Ella, V.B.; Jayag, O.P.; Cabangon, R.J.; Bouman, B.A.M. Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in central luzon, Philippines. Paddy Water Environ. 2015, 13, 215–227.
18. Mao, Z. Water efficient irrigation and environmentally sustainable irrigated rice production in China, International Commission on Irrigation and Drainage. https://www.icid.org/wat_mao.pdf, 2001 (Accessed 20 February 2023)
19. Ishfaq, M.; Farooq, M.; Zulfiqar, U.; Hussain, S.; Anjum, S.A. Alternate wetting and drying: a water-saving and ecofriendly rice production system. Agr. Water Manage. 2020, 241,106363.
20. Bouman, B.A.M.; Tuong, T.P. Field water management to save water and increase its productivity in irrigated lowland rice. Agric. Water Manage. 2001, 49, 11–30.
21. Sudhir, Y.; Evangelista, G.; Fardnilo, J.; Humphreys, E.; Henry, A.; Fernandez, L. Establishment method effects on crop performance and water productivity of irrigated rice in the tropics. Field Crop. Res. 2014, 166, 112–127.
22. Antic-Mladenovic, S.; Frohne, T.; Kresovic, M.; Stark, H.J.; Tomic, Z.; Licina, V.; Rinklebe, J. Biogeochemistry of Ni and Pb in a periodically flooded arable soil: fractionation and redox-induced (im)mobilization. J. Environ. Manag. 2017, 186, 141–150.
23. Li, X.; Rui, J.; Mao, Y.; Yannarell, A.; Mackie, R. Dynamics of the bacterial community structure in the rhizosphere of a maize cultivar. Soil Biol. Biochem.2014, 68, 392–401.
24. Li, H.F.; Lombi, E.; Stroud, J.L.; McGrath, S.P.; Zhao, F.J. Selenium speciation in soil and rice: influence of water management and Se fertilization. J. Agric. Food Chem. 2010, 58, 11837–11843.
25. Amundson, R.; Biardeau, L. Soil carbon sequestration is an elusive climate mitigation tool. PNAS.2018, 115, 11652-11656.
26. Peyron, M.; Bertora, C.; Pelissetti, S.; Pullicino, S.D.; Celia, L.; Miniotti, E.; Romani, M.; Sacco, D. Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. Agric. Ecosy. Environ. 2014, 232, 17–28.
27. Nan, Q.; Wang, C.; Wang, H.; Yi, Q.; Wu, W. Mitigating methane emission via annual biochar amendment pyrolyzed with rice straw from the same paddy field, Sci. Total Environ. 2020, 746, 141351.
28. Miyamoto, N.; Steudle, E.; Hirasawa, T.; Lafitte, R. Hydraulic conductivity of rice roots. J. Exp. Bot. 2001, 52 (362) 1835–1846.
29. Stiller, V.; Lafitte, H.R.; Sperry, J.S. Hydraulic Properties of Rice and the Response of Gas Exchange to Water Stress. Plant Physiol. 2003, 132, 1698–1706.

 doi:10.20944/preprints202311.1677.v1

30. Hubbard, R.M.; Stiller, V.; Ryan, M.G.; Sperry, J.S.Stomatal conductance and photosynthesis vary linearly with plant hydraulic conductance in ponderosa pine. Plant Cell Environ. 2001, 24, 113–121.
31. Tanguilig, V.C.; Yambao, E.B.; Toole, J.C.; De Datta, S.K. Water stress effects on leaf elongation, leaf water potential transpiration and nutrient uptake of rice, maize, and soybean. Plant Soil. 1987, 103, 155–168.
32. Shekhar, S.; Mailapalli, R.D.; Raghuwanshi, S.N.; Das, S.B. Hydrus-1D model for simulating water flow through paddy soils under alternate wetting and drying irrigation practice. Paddy and Water Environ. 2019, 18, 73–85.
33. Watanabe, T. Paddy Fields as Artificial and Temporal Wetland, Book Chapter 9, Irrigations in ecosystems. http://dx.doi.org/10.5772/intechopen.80581 (Accesed 20th, April, 2023).
34. Odhiambo, L.O.; Murty, V.V.V.Modeling water balance components in relation to field layout in lowland paddy fields. I. Model development. Agric. Water Manage. 1996, 30, 185-199.
35. Bouman, B.A.M.; Lampayan, R.M.; Tuong, T.P. Water management in irrigated rice: Coping with Water scarcity. International Rice Research Institute, Los Banos, Philipines, 2007; 54 p.
36. Maclean, J.L.; Dawe, D.; Hardy, B.; Hettel, G.P. Rice almanac: Source book for the most important economic activity on Earth (3rd ed.). International Rice Research Institute, Los Banos, Philippines 2002, 257p.
37. Ranjan, R.; Pranav, P.K. Cost analysis of manual bund shaping in paddy fields: Economical and physiological. Res. Agric. Eng. 2021, 67, 181–189.
38. Kim, S.J.; Park, G.A.; H.J. Kwon, H.J. Evaluation of Paddy Water Storage Dynamics during Flood Period in South Korea, KSCE J. Civil Eng. 2007, 17, 269-276.
39. Suozhu, M.B.; Sayed, M.; Senge. The Impact of Various Environmental Changes Surrounding Paddy Field on Its Water Demand in Japan, Rev. Agric. Sci. 2020, 8, 199–215.
40. Huanga, H.C.; Liua, C.W.; Chen, S.; Chen, J.S. Analysis of percolation and seepage through paddy bunds. J. Hydro. 2003, 284, 13–25.
41. Hatfield, L.H.; Dold, C. Water-Use Efficiency: Advances and Challenges in a Changing Climate. Front. Plant Sci. 2019, 10, 103.
42. Nie, L.; Peng, S.; Chen, M.; Shah, F.; Huang, J.; Cui, K.; Xiang, J. Aerobic rice for water-saving agriculture: A review. Agron. Sustain. Dev. 2012, 32, 411–418.
43. Tabbal, D.F.; Bouman, B.A.M.; Bhuiyan, L.S.; Sibayan, B.E.; Sattar, A.M. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric. Water Manag. 2002, 56, 93–112.
44. Parent, B.; Suard, B.; Serraj, R.; Tardieu, F. Rice leaf growth and water potential are resilient to evaporative demand and soil water deficit once the effects of root system are neutralized. Plant, Cell Environ. 2010, 33, 1256–1267.
45. Li, S.; Zuo, Q.; Wang, X.; Ma, W.; Jin, X.; Shi, J.; Ben-Gal, A. Characterizing roots and water uptake in a ground cover rice production system. PLoS One, 2017, 12, 1–18.
46. Matsuo,N.; Ozawa, K.; Mochizuki, T. Genotypic differences in root hydraulic conductance of rice (Oryza sativa L.) in response to water regimes. Plant Soil, 2009, 316, 25–34.
47. Kato, Y.; Okami, M. Root growth dynamics and stomatal behavior of rice (Oryza sativa L.) grown under aerobic and flooded conditions. F. Crop. Res. 2010, 117, 9–17.
48. Chen, S.K.; Liu, C.W.; Huang, H.C. Analysis of water movement in paddy rice fields (II) simulation studies. J. Hydro. 2002, 268, 259–271.
49. Yukawa, K.The fluctuation of irrigation requirement for paddy fields. Proceedings, International Workhop, Asian Institute of Technology, Thailand, 1992; pp. 32-42.
50. Prasanthkumar, K.; Saravanakumar, M.; Gunasekar, J.J. Water Management through Puddling Techniques, J Krishi Vigyan. 2019, 8 , 297-300.
51. Kalita, J.; Ahmed, P.; Baruah, N. Puddling and its effect on soil physical properties and growth of rice and post rice crops: A review. J. Pharmacogn. Phytochem. 2020, 9, 503-510.
52. Sharma, K.P.; De Datta, S.K. Effects of puddling on soil physical properties and processes, In. Soil Physics and Rice Book, International Rice Research Institute, Los Banos, Philippine, 1985; pp. 224-241.
53. Wopereis, M.C.S.; Wosten, J.H.M.; Bouma, J.; Woodhead, T. Hydraulic resistance in puddled rice soils-measurement and effects on water-movement. Soil Tillage Res. 1992, 24, 199–209.
54. Salokhe, V.M.; Shirin, A.K.M. Effect of puddling on soil properties: a review, Proceedings of the international Workshop, Asian Institute of Technology, Bangkok, Thailand, 1992; pp. 276-285.
55. Patil, M.D.; Das, B.S. Assessing the effect of puddling on preferential flow processes through under bund area of lowland rice field, Soil and Tillage Res. 2013, 134, 61-71.
56. Wopereis, M.C.S.; Bouman, B.AM.; Kropff, M.J.; ten Berge, H.F.M.; Maligaya, A.R. Water use efficiency of flooded rice fields I: Validation of the soil-water balance model SA WAH. Agric. Water Manage. 1994, 26, 277-289.
57. Beven, K.J.; Germann, P. Macropores and water flow in soils revisited. Water Resour. Res. 2013, 49, 3071–3092.

58. Bottinelli, N.; Zhou, H.; Boivin, P.; Zhang, Z.B.; Jouquet, P.; Hartmann, C.; Peng, X. Macropores generated during shrinkage in two paddy soils using X-ray micro-computed tomography. Geoderma. 2016, 265, 78–86.
59. Tuong, T.P.; Wopereis, M.C.S; Marquez, J.A.; Kropff, M.J. Mechanisms and control of percolation losses in irrigated puddled rice fields. SSA J. 1994, 58 , 1794-1803.
60. Fujihara, Y.; Yamada, R.; Oda, M.; Fujii, H.; Ito, O.; Kashiwagi, J. Effects of puddling on percolation and rice yields in rainfed lowland paddy cultivation: Case study in Khammouane province, central Laos. Agric. Sci. 2013, 4, 360-368.
61. Adachi, K. Effect of puddling on rice physical: Softness of puddled soil on percolation. Proceedings, International Workshop of Soil and Water Engineering for Paddy Field Management, Asian Institute of Technology, Bangkok, Thailand, 1992; pp.220-231.
62. Xu, B.; Shao, D.; Fang, L.; Yang, X.; Chen, S.; Gu, W.Modelling percolation and lateral seepage in a paddy field-bund landscape with a shallow groundwater table. Agric. Water Manage. 2019, 214, 87-96.
63. Sharma, P.K.; De Datta, S.K. Response of wetland rice to percolation under tropical conditions. Proceedings, International workshop, Soil and Water Engineering for paddy field management, Asian Institute of Technology, Bangkok, Thailand, 1992, pp. 109-117.
64. Wickham, T.H.; Singh, V.P. Water movement through wet soils, In: Soils and Rice. International Rice Research Institute (IRRI), Los Banos, Philippines,1978; pp. 337-357.
65. Hasegawa, S.; Thangaraj, M.; O'Toole, J.C. Root behavior: field and laboratory for rice and non-rice crops, In Soil Physics and Rice, International Rice Research Institute (IRR), Los Banos, Philippine, 1985, pp. 383-395.
66. Mizutani, M. Positive studies on the formation of surplus water requirement (Part 3)-On the variable characteristic of net water requirement-, Bulletin of the Faculty of Agriculture, Mie University, 1980, 61, 65–96.
67. Fujii, D.; Yamamoto, T.; Inoue, T.; Nagasawa, T. Change in water use by irrigation system from open channel to pipeline. Abstract, Meeting of the Japanese Society of Irrigation, Drainage and Rural Engineering, 2009, 436–437.
68. Tuong, T.P. Technologies for efficient utilization of water in rice production, In: Advances in Rice Science (K. S. Lee, K. K. Jena, and K. L. Heong, Eds.), Proceedings, International Rice Science Conference, Korea, Soul, Korea, 2004, pp. 141–161.
69. Tuong, T.P.; Bouman, B.A.M; Mortimer, M. More rice, less water–integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod. Sci. 2005, 8, 229-239.
70. Lawlor, D.; Tezara, W. Causes of decreased photosynthetic rate and metabolic capacity in water-deficient leaf cells: a critical evaluation of mechanisms and integration of processes. Annals of Botany. 2009, 103, 561–579.
71. Yoshino, M. Climatic Change and Rice Yield and Production in Japan during the Last 100 Years. Geographical Review of Japan. 1993, 66, 70-88.
72. Shelley, J.I.; Nosaka, M.T.; Nakata, M.K.; Haque, M.S.; Inukai, Y. Rice Cultivation in Bangladesh: Present Scenario, Problems, and Prospects. J Intl Cooper Agric. Dev. 2016, 14, 20–29.
73. Samejima, H.; Katsura, K.; Kikuta, M.; Njinju, M.S.; Kimani, M.J.; Yamauchi, A.; Makiwara,D. Analysis of rice yield response to various cropping seasons to develop optimal cropping calendars in Mwea, Kenya. Plant Prod. Sci. 2020, 23, 297-305.
74. Nayar, N.M. Origin of African Rice, Book Chapter, 5: In Origin and Phylogeny of Rices. Academic Press, Massachusetts, US, 2014; pp 117-168.
75. Odhiambo, L.O.; Murty, V.V.N. Water Management in Paddy Fields in Relation to Paddy Field Layout. Proceedings, International Workshop on Soil and Water Engineering, For Paddy Field Management, Asian Institute of Technology, Bangkok, Thailand, 1992; pp. 377-384.
76. Stoop, W.; UphoV, N.; Kassam, A. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: Opportunities for improving farming systems for resource - poor farmers. Agric. Syst. 2002, 71, 249 - 274.
77. Berkhout, E.; Glover, D.; Kuyvenhoven, A. On-farm impact of the System of Rice Intensification (SRI): Evidence and knowledge gaps. Agric. Sys. 2015, 132, 157–166.
78. UphoV, N.; Fernandez, E.; Long-Pin, Y.; Jiming, P.; Sebastien, R.; Rabenanadrasana, J. Assessments of the system of rice intensification (SRI). Proceedings, International Conference, Sanya, China, 2002.
79. Bwire, D.; Saito, H.; Okiria, O. Analysis of the impacts of irrigation practices and climate change on water availability for rice production: A case in Uganda. J. Arid Land Studies. 2022, S, 116-121.
80. Bouman, B.A.M.; Humphreys, E.; Tuong, T.P.; Barker, R. Rice and Water, In Advances for Agronomy, 2007, 92, 187-237.
81. Katambara, Z.; Kahimba, F.C.; Mahoo, H.F.; Mbungu, W.B.; Mhenga, F.; Reuben, P.; Maugo, M.; Nyarubamba, A. Adopting the system of rice intensification (SRI) in Tanzania: A review, Ag. Sci. 4 (2013). https://doi.org/10.4236/as.2013.48053.

 doi:10.20944/preprints202311.1677.v1

82. Lampayan, M.R.; Yadav, S.; Humphreys, E. Saving Water with Alternate Wetting Drying (AWD). International Rice Research Institute (IRRI). http://www.knowledgebank.irri.org/training/fact-sheets/water-management/saving-water-alternate-wetting-drying-awd, 2005 (Accessed 3rd February 2023).
83. Balasubramanian, V.; Hill, J.E. Direct seeding of rice in Asia: emerging issues and strategic research needs for the 21st century, In. Book, Direct Seeding: research strategies and opportunities, IRRI, 2002; pp. 21-45.
84. Cabangon, R.J.; Tuong, T.P.; Abdullah, N.B Comparing water input and water productivity of transplanted and direct-seeded rice production systems. Agric. Water Manage. 2002, 57, 11–31.
85. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, F.J.; Pretty, J.; Robinson, S.; Thomas, M.S.; Toulmin, C. Food security: the challenge of feeding 9 billion people. Sci. 2010, 327, 812–818.
86. Brown, M.E.; Funk, C.C. Food security under climate change. Scie. 2008, 319 (5863) 580–581.
87. Dananjaya, P.K.V.S.; Shantha, A.A.; Patabendi, K.P.L.N. Impact of Climate Change and Variability on Paddy Cultivation in Sri Lanka, Systematic Review. Res. Square, 2022, 1-13.
88. Enete, A.; Amusa, T. Challenges of Agricultural Adaptation to Climate Change in Nigeria: ASynthesis from the Literature, Fact Reports. Open Edi. J. 4 (2016) 0-11.
89. Lemi, T.; Hailu, F. Effects of Climate Change Variability on Agricultural Productivity. Intl. J. Environ. Sci. Nat. Res. 2019, 17, 14-20.
90. Haile, G.G.; Tanga, Q.; Suna, S.; Huanga, S.; Zhanga, X.; Liu, X. Droughts in East Africa: Causes, impacts and resilience. Earth-Sci. Rev. 2019, 193, 146-161.
91. Mall, R.K.; Aggarwal, P.K. Climate Change and Rice Yields in Diverse Agro-Environments of India. II: Effect of Uncertainties in Scenarios and Crop Models on Impact Assessment. Climatic Change. 2002, 52, 331–343.
92. Zhang, S.; Tao, F. Modeling the response of rice phenology to climate change and variability in different climatic zones: Comparisons of five models. Eur. J. Agron. 2013, 45, 165–176.
93. Chen, C.C.; McCarl, B.; Chang, C.C. Climate change, sea level rise and rice: Global market implications. Climatic Change, 2011, 110, 543–560.
94. Ayugi, B.; Eresanya, O.E.; Onyango, O.A.; Ogou, F.K.; Okoro, C.E.; Okoye, O.C.; Anoruo, M.C.; Dike, N.V.; Ashiru, R.O.; Daramola, T.M.; Mumo, R.; Ongoma, V. Review of Meteorological Drought in Africa: Historical Trends, Impacts, Mitigation Measures, and Prospects. Pure Appl. Geophys. 2022, 179, 1365-1386.
95. Gornall, J.; Betts, R.; Burk, E.; Clark, R.; Camp, J.; Willett, K.; Wilshire, A. Implications of climate change for agricultural productivity in the early twenty-first century. Biol. Sci. 2010, 365 (1554) 2973-2989.
96. Rahman, A.N.M.R.; Zhang, J. Trends in rice research: 2030 and beyond. Food and Energy Sec. 2022, 12, 1-17.
97. GRiSP (Global Rice Science Partnership), In. BooK: Rice almanac, 4th Edition.: International Rice Research Institute, Los Banos, Phillippines, 2013; 283 p.
98. Roudier, P.; Sultan, B.; Quirion, P.; Berg, A. The impact of future climate change on West African crop yields: What does the recent literature say?. Glob. Environ. Chang. 2011, 21, 1073-1083.
99. F. Terdoo, F.; Feola, G. The Vulnerability of Rice Value Chains in Sub-Saharan Africa: A Review. Climate, 2016, 4 (3) 47;.
100. S. Prabnakorn, S.; Maskey, S.; Suryadi, F.X.; De Fraiture, C. Rice yield in response to climate trends and drought index in the Mun River Basin, Thailand. Sci. Total Environ. 2018, 621, 108–119.
101. Kontgisa, C.; Schneidera, A.; Ozdogana, M.; Kucharika, C.; Trie, V.P.D.; Duce, H.D.; Schatzd, J. Climate change impacts on rice productivity in the Mekong River Delta. Appl. Geog. 2019, 102, 71–83.
102. R. Wassman, R.; Nelson, G.C.; Peng, S.B.; Sumfleth, K.; Jagadish, S.V.K.; Hosen, Y.; Rosegrant, M.W. Rice and global climate change, In: Rice in the global economy: Strategic research and policy issues for food security, Los Banos, Philippines: International Rice Research Institute (IRRI), 2010; pp. 411–431.
103. Wassmann, R.; Hien, N.X.; Hoanh, C.H.U.T.; Tuong, T.O.P. Sea level rise affecting the Vietnamese Mekong delta: Water elevation in the flood season and implications for rice production. Climatic Change, 2004, 66, 89–104. Kluwer Academic Publishers, Netherlands.
104. Pandey, S.; Paris, T.; Bhandari, H. Household income dynamics and changes in gender roles in rice farming. Book Chap.: Rice in the global economy: Strategic research and policy issues for food security, Los Banos, Philippines: International Rice Research Institute (IRRI), 2010; pp. 93–111.
105. Rowhani, P.; Lobell, D.B.; Linderman, M.; Ramankutty, N. Climate variability and crop production in Tanzania. Agric. For. Meteorol. 2011, 151, 449–460.
106. Kima, A.S.; Traore, S.; Wang, Y.M.; Chung, W.G. Multi-genes programing and local scale regression for analyzing rice yield response to climate factors using observed and downscaled data in Sahel. Agric. Water Manage. 2014, 146, 149–162.
107. Ward, P.S.; Florax, R.J.G.M.; Flores-Lagunes, A. Climate change and agricultural productivity in Sub-Saharan Africa: A spatial sample selection model. Eur. Rev. Agric. Econ. 2014, 41, 199–226.
108. Nwalieji, H.U.; Uzuegbunam, C.O. Effect of climate change on rice production in Anambra State, Nigeria. J. Agric. Ext. 2012, 16, 81–91.

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109. Calzadilla, A.; Zhu, T.; Rehdanz, K.; Tol, R.S.J.; Ringler, C. Climate change and agriculture: Impacts and adaptation options in South Africa. Water Res. Econ. 2014, 5, 24–48.
110. Harvey, C.A.; Rakotobe, Z.L.; Rao, N.S.; Dave, R.; Razafimahatratra, H.; Rabarijohn, R.H.; Rajaofara, H.; Mackinnon, J.L. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. Philos. Trans. R. Soc. Lond. B Biol. Sci. 2014, 369 (1639), 1-12.
111. Ochieng, J.; Kirimi, L.; Mathenge, M. Effects of climate variability and change on agricultural production: The case of small-scale farmers in Kenya. J. Life Sci. 2016, 77 , 71-78.
112. Challinor, A.J.; Koehler, A.; Whitfield, S.; Das, B. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nat. Clim. Chang. 2016, 6, 954-958.
113. Okada, M.; Iizumi, T.; Hayashi, Y.; Yokozawa, M. Projecting climate change impacts both on rice quality and yield in Japan. J. Agric. Meteorol. 2011, 67, 285–95.
114. Morita, S.; Wada, H.; Matsue, Y. Countermeasures for heat damage in rice grain quality under climate change. Plant Prod. Sci. 2016, 19, 1–11.
115. Masutomi, Y.; Takimoto, T.; Shimamura, M.; Manabe, T.; Arakawa, M.; Shibota, N.; Ooto, A.; Azuma, S.; Imai., Y.; Tamura, M. Rice grain quality degradation and economic loss due to global warming in Japan. Environ. Res. Commun. 2019, 1, 121003
116. Triyanti, R.; Suryawati, S.H.; Wijaya, R.A.; Wardono. B.; Hafsaridewi, R. Assessment of the success factors influencing of
rice-fish farming innovation village to support food security. Earth and Environ. Sci. 892, 012052.
117. Juma, C. The New Harvest: Agricultural Innovation in Africa, Book, Oxford University Press, 2011, 258p. Oxford, United Kingdom.
118. Koide, J.; Fujimoto, N.; Okai, N.; Mostafa, H. Rice-fish Integration in Sub-Saharan Africa: The Challenges for Participatory Water Management, Review, JARQ, 2015, 49, 29-36.
119. Refaliarison, J.; National Aquaculture Sector Overview -Madagascar. FAO Fisheries and Aquaculture Department. http://www.fao.org/fishery/countrysector/naso_madagascar/ (Accessed 20th February 2023).
120. Halwart, M.; Gupta, M.V. Culture of fish in rice fields, Book, FAO & the World Fish Center, Penang, Malaysia, 2004, 83 p.
121. Bakker, M.; Matsuno, Y.A. Framework for Valuing Ecological Services of Irrigation Water – A Case of an Irrigation-Wetland System in Sri Lanka, Irri. Drainage Sys. 2001, 15, 99–115.
122. Halls, A.S.; Hoggarth, D.D.; Debnath, K. Impacts of hydraulic engineering on the dynamics and production potential of floodplain fish populations in Bangladesh. Fisheries Manag. Ecol. 1999, 6, 261-285.
123. Gowing, J.W. A review of experience with aquaculture integration in large-scale irrigation systems, In Integrated Irrigation and Aquaculture in West Africa–Concepts, Practices and Potential, M. Halwart A. van Dam, (eds), FAO, Rome, 2006, 12, 135-150.
124. Bene, C.; Arthur, R.; Norbury, H.; Allison, H.E.; Beveridge, M.; Bush, S.; Campling, L.; Leschen, W.; Little, D.; Squires, D.; Thilsted, H.S.; Troell, M.; Williams, M. Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. World Dev., 2016, 79, 177–196.
125. Li, K. Rice–fish farming systems in China: past, present, and future, In Rice–Fish Research and Development in Asia. ICLARM Conference, Proceedings, International Center for Living Aquatic Resources Management, Manila, Philippines, 1992; pp.17-26.
126. Brugere, C. A review of the development of integrated irrigation aquaculture (IIA), with special reference to West Africa. In Integrated Irrigation and Aquaculture in West Africa – Concepts, Practices and Potential, eds. Halwart, M. & van Dam, A., FAO, Rome, 2006, 4, 27-60.
127. Miller, J. The potential for development of aquaculture and its integration with irrigation within the context of the FAO Special Programme for Food Security in the Sahel. Proceedings, Integrated Irrigation and Aquaculture in West Africa-Concepts, Practices and Potential, FAO, Rome, 2006; pp. 61-74.
128. Peterson, J.; Kalende, M.; Sanni, D.; N'Gom, M. The potential for integrated irrigation aquaculture (IIA) in Mali. Proceedings, Integrated Irrigation and Aquaculture in West Africa-Concepts, Practices and Potential, FAO, Rome, Italy, 2006; pp. 79-93.
129. Pengseng, J. On-farm trial with rice-fish cultivation in Nakhon Si Thammarat Southern Thailand Walailak, J. Sci. Technol. 2013, 10, 67–75.
130. Pretty, J. Agricultural sustainability: concepts, principles, and evidence. Philos. Trans. R. Soc. B: Biol. Sci. 2007,363, 447–465.
131. Welcomme, R.; Bartley, D. Current approaches to the enhancement of fisheries. Fish. Manag. Ecol. 1998, 5, 351-382.
132. Koohafkan, P.; Furtado, J. Traditional rice fish systems and globally indigenous agricultural heritage systems, in FAO Rice Conference. http://www.fao.org/3/y5682e/y5682e0b.htm, 2004 (Accessed 21 February 2023).
133. Freed, S.; Barman, B.; Dubois, M.; Flor, R.J.; Funge-Smith, S.;, Gregory, R.; Hadi, B.; Halwart, M.; Haque, M.; Jagadish, S.V.K.; Joffre, O.M.; Karim, M.; Kura, Y.; McCartney, M.; Mondal, M.; Nguyen, V.K.; Sinclair, F.; Stuart, A.M.; Tezzo, X.; Yadav, S.; Cohen, P.J. Maintaining Diversity of Integrated Rice and Fish

 doi:10.20944/preprints202311.1677.v1

Production Confers Adaptability of Food Systems to Global Change. Front. Sustain. Food Syst. 2020, 4, 576179.
134. Borja, A. Grand challenges in marine ecosystems ecology. Front. Mar. Sci. 2014, 1, 1-6.
135. Nguyen, T.G. The use of zoobenthos for the assessment of water quality in canals influenced by landfilling and agricultural activity. J. Vietnam. Environ. 2019, 11, 33–42.
136. Song, H.; Lu, X.W.; X.-N. Li, Y.-F. Qin, The water purification effect of hydroponic biofilter method by artificial putting in zoobenthos. China Environ. Sci. 2007, 27, 58–61.
137. Takayoshi, Y.; Tuan, L.M.; Kazunori, M.; Shigeki, Y. Alternate Wetting and Drying (AWD) Irrigation Technology Uptake in Rice Paddies of the Mekong Delta, Vietnam: Relationship between Local Conditions and the Practiced Technology. Asian and African Area Studies, 2016, 15, 234-256.
138. Mote, K.; Rao, V.; Ramulu, P.V.; Kumar, V.K.; Devi, A.K.; Uma, M. Standardization of alternate wetting and drying (AWD) method of water management in lowland rice (oryza sativa l.) for upscaling in command outlets. Irrig. Drain. 2017, 67, 166-178.
139. IWMI, Alternate wetting and dry in Rice Cultivation. In Climate Adaptation through Innovation. https://www.nibio.no/en/projects/climaadapt/technical-briefs/_/attachment/inline/89cf553b-6cd4-4235-871d 1fa499f41129:a1f11777f5dfe8add4e297b5197576918002f05b/IWMI%20Book%20Final_AWD.PDF, 2014 (Accessed 21 February 2023).
140. Latif, A. A study on effectiveness of field water tube as a practical indicator to irrigate SRI Rice in Alternate wetting and drying irrigation management practice. M.Sc. Thesis, The Univ. of Tokyo. Japan, 2010.
141. Mote, K.; Praveen Rao, V.; Ramulu, V.; Kumar, A.K. Effectiveness of field water tube for standardization of alternate wetting and drying method of water management in lowland rice. Irri. Drain. J. 2019, 68, 679-689.
142. Pascual, V.J.; Wang, Y.M. Utilizing rainfall and alternate wetting and drying irrigation for high water productivity in irrigated lowland paddy rice in southern Taiwan. Plant Prod. Sci. 2017, 20, 24–35.
143. Lampayan, R.M.; Palis, F.G.; Flor, R.B.; Bouman, B.A.M.; Quicho, E.D.; De Dios, J.L.; Espiritu A.; Sibayan, E.B.; Vicmudo Lactaoen, A.T.; Soriano, J.B. Adoption and dissemination of "Safe Alternate Wetting and Drying" in pump irrigated rice areas in the Philippines, In: 60th International Executive Council Meeting of the International Commission on Irrigation and Drainage (ICID),5th Regional Conference, 2009.
144. Abrol, I.P.; Bhumbla, E.R.; Meelu, O.P. Influence of salinity and alkalinity on properties and management of rice lands, In: Book: Soil Physics and Rice. International Rice Research Institute, Los Banos, Philippines, 1985, pp. 430.
145. Yang, C.; Yang, L.; Yang, Y.; Ouyang, Z. Rice root growth and nutrient uptake influenced by organic manure in continuously and alternately flooded paddy soils. Agric. Water Manage. 2004, 70, 67–81.
146. Horie, T.; Shiraiwa, T.; Homma, K.; Katsura, K.; Maeda, S.; Yoshida, H. Can yields of lowland rice resume the increases that they showed in the 1980s?. Plant Prod. Sci. 2005, 8, 259–274.
147. Xu, Z.; Zhou, G.; Shimizu, H. Plant responses to drought and rewatering. Plant Signal. Behav. 2010, 5, 649–654.
148. Cabangon, R.J.; Tuong, T.P.; Castillo, E.G.; Bao, L.X.; Lu, G.; Wang, G.; Cui, Y.; Bouman, B.A.M.; Li, Y.; Chen, C.D.; Wang, J.Z. Effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. Paddy Water Env. 2004, 2, 195–206.
149. Yao, F.X.; Huang, J.L.; Cui, K.H.; Nie, L.X.; Xiang, J.; Liu, X.J. Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. Field Crops Res. 2012, 126, 16–22.
150. G. Mahajan, B.S. Chauhan, J. Timsina, P.P. Singh, K. Sing, Crop performance and water and nitrogen use efficiencies in dry seeded rice in response to irrigation and fertilizer amounts in northwest India, Field Crop Res. 134 (2012) 59–70. https://doi.org/10.1016/j.fcr.2012.04.011.
151. Cabangon, R.J.; Castillo, E.G.; Tuong, T.P. Chlorophyll meter-based nitrogen management of rice grown under alternate wetting and drying irrigation. Field Crops Res. 2011, 121, 136–146.
152. Nalley, L.L.; Linquist, B.; Kovacs, K.F.; Anders, M.M. The economic viability of alternate wetting and drying irrigation in Arkansas rice production. Agron. J. 2015, 107, 579–587.
153. Siopongco, J.D.L.C.; Wassmann, R.; Sander, B.O. Alternate wetting and drying in Philippine rice production: feasibility study for a clean development mechanism, IRRI Technical Bulletin No. 17. Los Banos, Philippines: International Rice Research Institute, 2013. 18 p.
154. Hamoud, Y.A.; Guo, .; Wang, Z.; Chen, S.; Rasool, G. Effects of irrigation water regime, soil clay content and their combination on growth, yield, and water use efficiency of rice grown in South China. Int. J. Agric. Biol. Eng. 2018, 11, 126–136.
155. USDA, Soil Taxonomy Report: A Basic System of Soil Classification for Making and Interpreting Soil Surveys; USDA-NRCS: Washington, DC, USA, 1999. https://www.nrcs.usda.gov/sites/default/files/2022-06/Soil%20Taxonomy.pdf (Accessed 27 February 2023).

 doi:10.20944/preprints202311.1677.v1

156. Haque, A.N.A.; Uddin, K.Md.; Sulaiman, F.M.; Amin, M.A.; Hossain, M.; Solaiman, M.Z.; Mosharrof, M. Biochar with Alternate Wetting and Drying Irrigation: A Potential Technique for Paddy Soil Management. Agric. 2021, 11, 367.
157. Dinka, T.M.; Lascano, R.J. Review Paper: Challenges and Limitations in Studying the Shrink-Swell and Crack Dynamics of Vertisol Soils. Open J. Soil Sci. 2012, 2, 82–90.
158. Sander, T.; Gerke, H.H. Preferential flow patterns in paddy fields using a dye tracer. Vadose Zone J. 2007, 6, 105–115.
159. Yoshida, S.; Adachi, K. Numerical analysis of crack generation in saturated deformable soil under-row-planted vegetation. Geoderma. 2004, 120, 63–74.
160. Tan, X.; Shao, D.; Liu, H.; Yang, F.; Xiao, C.; Yang, H. Effects of alternate wetting and drying irrigation on percolation and nitrogen leaching in paddy fields. Paddy Water Environ. 2013, 11, 381–395.
161. Stewart, R.D.; Najm, M.R.A.; Rupp, D.E.; Lane, J.W.; Uribe, H.C.; Arumi, J.L.; Selker, J.S. Hillslope run-off thresholds with shrink-swell clay soils. Hydrol. Process. 2015, 29, 557–571.
162. Liu, C.W.; Cheng, S.W.; Yu, W.S.; Chen, S.K. Water infiltration rate in cracked paddy soil. Geoderma. 2003, 117, 169–181.
163. Jarvis, N.J. A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. Eur. J. Soil Sci. 2007, 58, 523–546.
164. Hardie, M.A.; Cotching, W.E.; Doyle, R.B.; Holz, G.; Lisson, S.; Mattern, K. Effect of antecedent soil moisture on preferential flow in a texture-contrast soil. J. Hydro. 2011, 398, 191–201.
165. Sidle, R.C.; Kardos, T.L.; Genuchten, Van.M.Th. Heavy metals transport model in a sludge-treated soil. J. Environ. Qual. 1977, 6, 438-443.
166. Watson, K.; Luxmoore, R. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. SSA J. 1986, 50, 578–582.
167. Wilson, G.; Luxmoore, R. Infiltration, macroporosity, and mesoporosity distributions on two forested watersheds. SSA J. 1999, 52, 329–335.
168. Price, H.A.; Norton, G.J.; Salt, D.E.; Ebenhoeh, O.; Meharg, A.A; Meharg, C.; Islam, M.R.; Sarma, R.N.; Dasgupta, T.; Ismail,A.M.; McNally, K.L.; Zhang, H.; Dodd, I.C.; Davies, W.J. Alternate wetting and drying irrigation for rice in Bangladesh: Is it sustainable and has plant breeding something to offer?. Food and Energy Secur.2013, 2, 120–129.
169. Li, H.F.; Lombi, E.; Stroud, J.L.; McGrath, S.P.; Zhao, F.J. Selenium speciation in soil and rice: influence of water management and Se fertilization. J. Agric. Food Chem. 2010, 58, 11837–11843.
170. Xu, X. Y.; McGrath, S.P.; Meharg, A.A.; Zhao, F.J. Growing rice aerobically markedly decreases arsenic accumulation. Environ. Sci. Technol. 20008, 42, 5574–5579.
171. Norton, G.J.; Pinson, S.R.M.; Alexander, J.; Mckay, S.; Hansen, H.; Duan, G.L.; Islam, R.M.; Stroud, L.J.S.; Zhao, F-Jie.; McGrath, S.P.; Zhu, Y.G.; Lahner, B.; Yakubova, E.; Guerinot, L.M.; Tarpley, L.; Eizenga, C.G.; Salt, E.D.; Meharg, A.A.; Price, H.A. Variation in grain arsenic assessed in a diverse panel of rice (Oryza sativa) grown in multiple sites. New Phytol. 2012, 193, 650–664.
172. Brammer, H.; Ravenscroft, P. Arsenic in groundwater: a threat to sustainable agriculture in South and South-East Asia. Environ. Int. 2009, 35, 47–654.
173. Pentrakova, L.; Su, K.; Pentrak, M.; Stucki, J.W. A review of microbial redox interactions with structural Fe in clay minerals. Clay Miner. 2013, 48, 543–560.
174. Schneiders, M.; Scherer, H. Fixation and release of ammonium in flooded rice soils as affected by redox potential. Eur. J. Agron. 1988, 8, 181–189.
175. Cucu, M.A.; Said-Pullicino, D.; Maurino, V.; Bonifacio, E.; Romani, M.; Celi, L. Influence of redox conditions and rice straw incorporation on nitrogen availability in fertilized paddy soils. Biol. Fert. Soils, 2014, 50, 755–764.
176. Pandey, S.; Yadav, S.; Hellin, J.; Balie, J.; Bhandari, H.; Kumar, A.; Mondal, A.K. Why Technologies Often Fail to Scale: Policy and Market Failures behind Limited Scaling of Alternate Wetting and Drying in Rice in Bangladesh. Water, 2020, 12, 1510.
177. Rejesus, R.M.; Palis, F.G.; Rodriguez, D.G.P.; Lampayan, R.M.; Bouman, B.A.M. Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: evidence from rice producers in the Philippines. Food Policy. 2011, 36 280–288.
178. Kirk, G.J.D. The biogeochemistry of submerged soils, Book. Wiley, Chichester, England, 2004, 304P.
179. Arao, T.; Kawasaki, A.; Baba, K.; Mori, S.; Matsumoto, S. Effects of water management on Cadmium and Arsenic accumulation and Dimethylarsinic acid concentrations in Japanese rice. Environ. Sci. Technol. 2009, 43, 9361–9367.
180. Yang, J.C.; Huang, D.; Duan, H.; Tan, G.; Zhang, J. Alternate wetting and moderate drying increase grain yield and reduces cadmium accumulation in rice grains. J. Sci. Food Agric. 2009, 89, 1728–1736.
181. Meharg, A. A.; Norton, G.; Deacon, C.; Williams, P.; Adomako, E.E.; Price, A.; Zhu, Y.; Li, G.; Zhao, F.J.; McGrath, S.; Villada, A.; Sommella, A.; De Silva, P.M.C.S.; Brammer, H.; Dasgupta, T.; Islam, M.R.Variation in rice cadmium related to human exposure. Environ. Sci. Technol. 2013, 47, 5613–5618.

182. Arenas-Calle, N.L.; Whitfield, S.; Challinor, J.A. A Climate Smartness Index (CSI) Based on Greenhouse Gas Intensity and Water Productivity: Application to Irrigated Rice. Front. Sustain. Food Syst. 2019, 3, 105.
183. Uprety, D.C.;. Dhar, S.; Hongmin, D.; Kimball, B.A.; Garg, A.; Upadhyay, J. Technologies for Climate Change Mitigation - Agriculture Sector, UNEP Riso Centre on Energy, Climate and Sustainable Development. Department of Management Engineering. Technical University of Denmark (DTU), TNA Guidebook Series, 2012.
184. IPCC, Summary for Policymakers, In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://archive.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf, 2011, (Accessed 27 February 2023).
185. Kumar, M.; Nandini, N. Greenhouse Gas Emissions from Rice Fields of Bengaluru Urban District, India. Department of Environmental Science, Bangalore University, Jnana Bharathi campus, Bengaluru, Karnataka, INDIA. Int. J. Environ. Agric. Res. 2016, 2, 39-43.
186. Runkle, B.; Suvocarev, K.; Reavis, C.; Reba, M.L. Carbon dynamics and the carbon balance of rice fields in the growing season, Abstract #B33G-2745, American Geophysical Union, Fall Meeting 2018.
187. Lal, R. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. L. Degrad. Dev. 2005, 17, 197–209.
188. Grace, P.R.; Harrington, L.; Jain, M.C.; Robertson, G.P. Longterm sustainability of the tropical and subtropical rice-wheat system: an environmental perspective, In Improving the Productivity and Sustainability of Rice-Wheat System: Issues and Impacts American Society of Agronomy Special Publication 65 ed J K Ladha et al (Madison, WI: American Society of Agronomy), 2003, pp. 27–43.
189. Livsey, J.; Katterer, T.; Vico, G.; Lyon, W.S.; Lindborg, R.; Scaini1, A.; Thi Da, T.; Manzon, S. Do alternative irrigation strategies for rice cultivation decrease water footprints at the cost of long-term soil health? Environ. Res. Lett. 2019,14, 074011.
190. Pham, V.B.; Diep, T.T.; Fock, K.; Nguyen, S.T. Using the Internet of Things to promote alternate wetting and drying irrigation for rice in Vietnam's Mekong Delta. Agron. Sustain. Dev. 2021, 41 (3) 43.
191. Nelson, A.; Wassmann, R.; Sander, B.O.; Palao, L.K. Climate-Determined Suitability of the Water Saving Technology "Alternate Wetting and Drying" in Rice Systems: A Scalable Methodology demonstrated for a Province in the Philippines. PLoSONE, 2015, 10, 1-19.
192. Akpoti, K.; Dossou-Yovo, R.E.; Zwart, J.S.; Kiepe, P. The potential for expansion of irrigated rice under alternate wetting and drying in Burkina Faso. Agric. Water Manage., 2021, 247, s106758.
193. Lin, H.C.; Richards, D.R.; Yeh, G.T.; Cheng, J.R.; Cheng, H.P.; Jones, N.L.; FEMWATER: a three-dimensional finite element computer model for simulating density dependent flow and transport, Technical Report, HL-96, 1996.
194. Li, Y.; Simunek, J.; Jing, L.; Zhang, Z.; Ni, L. Evaluation of water movement and Water Losses in a direct-seeded-rice field experiment using Hydrus-1D, Agric. Water Manage. 2014, 142, 38-46.
195. Tan, X.; Shao, D.; Liu, H. Simulating soil water regime in lowland paddy fields under different water managements using HYDRUS-1D. Agric. Water Manage. 2014, 132, 69–78.
196. Jackson, R.D.; Idso, S.B.; Reginato, R.J.; Pinter, P.J. Canopy temperature as a crop water stress indicator. Water Resource Res. 1981, 17, 1133–1138.
197. Irmak, S.; Haman, Z.D.; Bastug, R. Determination of crop water stress index for irrigation timing and yield estimation of corn. Agron. J. 2000, 92, 1221–1227.
198. Taghvaeian, S.; Comas, L.; DeJonge, K.C.; Trout, T.J. Conventional and simplified canopy temperature indices predict water stress in sunflower. Agric. Water Manag. 2014, 144, 69–80.
199. Katimbo, A.; Rudnick R.D.; DeJonge, C.K.; Him Lo, T.; Qiao, X.; Franz, E.T.; Nakabuye N.H.; Duan, J. Crop water stress index computation approaches and their sensitivity to soil water dynamics. Agric. Water Manage. 2022, 266, 107575.
200. Gadal, N.; Shrestha, J.; Poudel, N.M.; Pokharel, B. A review on production status and growing environments of rice in Nepal and in the world. Archives Agric. Environ. Sci. 2019, 4, 83-87.
201. Khus, G.S. Terminology for Rice Growing environments. International rice Research Institute (IRRI), Los Banos, Philippines. https://pdf.usaid.gov/pdf_docs/PNAAR582.pdf, 1984 (Accessed 10 April 2023).
202. Cultivation practices: Water Management, Tamil Nadu University, India. http://www.agritech.tnau.ac.in/expert_system/paddy/cultivationpractices3.html (Accessed 29 March 2023).
203. Thakur, A.K.; Roychowdhury, S.; Kundu, D.K.; Singh, R. Evaluation of planting methods in irrigated rice. Arch. Agron. Soil Sci. 2005, 50, 631–640.
204. World rice production, Consumption and Stocks, USDA. https://apps.fas.usda.gov/psdonline/reporthandler.ashx?reportId=681&templateId=7&format=html&fileName=World%20Rice%20Production,%20Consumption,%20and%20Stocks (Accessed 29 March 2023).
205. Chapagain T.; Yamaji, E. The effects of irrigation method, age of seedling and spacing on crop performance, productivity, and water-wise rice production in Japan. Paddy Water Env. 2010, 8, 81–90.

206. Rahman, R.; Sheikh, H.B. Effect of alternate wetting and drying (AWD) irrigation for Boro rice cultivation in Bangladesh. Agric. Fores. Fisheries, 2014, 3, 86–92.
207. Ganesh, H.V. Effect of various irrigation schedules on yield and water use in transplanted paddy. Mysore. J. Agric. Sci. 2000, 34, 222–226.
208. Zhao, L.M.; Wu, L.H.; Li, Y.S.; Sarkar, A.; Zhu, D.F.; Uphoff, N. Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the System of Rice Intensification. Commun. Soil Sci. Plant Anal. 2010, 4, 1–12.
209. Yang, J.C.; Zhang, J.H. Crop management techniques to enhance harvest index in rice. J Exp Bot 2010, 61, 3177–3189.
210. Mote, K. Standardization of Alternate Wetting and Drying (AWD) method of water management in low land rice (O. sativa L.) for up scaling in command outlets. Ph.D. Thesis. Submitted to Professor Jayashankar Telangana State Agriculture University, Hyderabad, Telangana, India, 2016.
211. Omwenga, K.G.; Mati, B.M.; Home, P.G. Determination of the effect of the System of Rice Intensification (SRI) on rice yields and water saving in Mwea irrigation scheme, Kenya. J. Water Res. Prote. 2014, 6, 895–901.
212. Paul, P.L.C.; Rashid, M.A.; Paul, M. Refinement of Alternate wetting and drying irrigation method for rice cultivation. Bangladesh Rice J. 2013, 17, 33–37.
213. Ashouri, M. Water use efficiency, irrigation management and nitrogen utilization in rice production in the north of Iran. APCBEE Proc. 2014, 8, 70–74.
214. Sariam, O.; Anua, A.R. Effects of irrigation regime on irrigated rice. J. Trop. Agric. Food Sci. 2010, 38, 1–9.
215. Buresh, R.J. Nutrient best management practices for rice, maize, and wheat in Asia. World Congress of Soil Science, Brisbane, Australia, 1–6 August 2010.
216. Siad, M.S.; Iacobellis, V.; Zdruli, P.; Gioia, A.; Stavi, I.; Hoogenboom, G. A review of coupled hydrologic and crop growth models. Agric. Water Manage. 2019, 224, 105746.
217. Kimball, B.A. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron. J. 1983, 75, 779–788.
218. Bachelet, D.; Gay, C.A. The impacts of climate change on rice yield: A comparison of four model performances. Ecological Modelling, 1993, 65, 71–93.
219. Erda, L.; Wei, X.; Hui, J.; Yinlong, X.; Yue, L.; Liping, B.; Liyong, X. Climate change impacts on crop yield and quality with CO_2 fertilization in China. Biol. Sci. 2005, 360, 2149–2154.
220. Gerardeaux, E.; Giner, M.; Ramanantsoanirina, A.; Dusserre, J. Positive effects of climate change on rice in Madagascar. Agron. Sust. Dev.2011, 32, 619–627.
221. Palis, F.G.; Cenas, P.A.; Bouman, B.A.M.; Lampayan, R.M.; Lactaoen, A.T.; Norte, T.M.; Vicmudo, V.R.; Hossain, M.; Castillo, G.T. A farmer participatory approach in the adaptation and adoption of controlled irrigation for saving water: a case study in Canarem, Victoria, Tarlac, Philippines. Philipp. J. Crop Sci. 2004, 29, 3-12.
222. Emission by sector, Our World in Data. https://ourworldindata.org/emissions-by-sector, 2023 (Accessed 3 May 2023).
223. Bwire, D.; Saito, H.Influence of Alternate Wetting and Drying Irrigation Conditions on Soil Redox Potential, Water productivity and Agronomic Performance of Paddy Rice. Proceeding, 72nd meeting of Japanese Society of Irrigation, Drainage and Rural Engineering, Kanto Region, 2021, book of abstract, pp. 16-20.