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# Water Management and Hydrological Characteristics of Paddy-Rice Fields under Alternate Wetting and Drying Irrigation Practice as Climate Smart Practice: A Review

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**Abstract:** Paddy-rice cultivation using the traditional continuous flooding method requires much water, up to 2500 L, to produce 1 kg of rice. Decreasing water availability is being exacerbated by climate dynamics, i.e., droughts and rainfall variability negatively affecting food security in developing regions, particularly Africa. Alternate wetting and drying (AWD) practice is a climate-smart water management strategy that, together with puddling (a critical field preparation process), significantly affects soil hydrological and physicochemical regimes, such as soil water dynamics and oxidation states in paddy fields. However, there are limited reviews on the effects and interaction of the AWD duration on hydrological conditions in the paddy-rice rhizosphere continuum under AWD practice at different rice growth stages. Our review synthesizes key scientific literature to examine water management and hydrological properties of paddy soils under AWD practice with climate change and sheds light on why farmers are skeptical in adopting the practice. To develop this paper, we reviewed scientific information from published journal articles, reliable reports, and our knowledge on paddy-rice cultivation and water management with climate change in Asia and Sub-Saharan Africa. Several studies confirm that AWD practice increases water–rice–crop productivity, yields, and reduces methane emissions. Limitations and challenges of AWD irrigation, including changes in soil structure that influence irrigation water application, variations in hydraulic conductivity caused by the duration and frequency of irrigation cycles, and frequent manual water level (WL) monitoring, are discussed. Opportunities to improve the integration of AWD strategies within government policies, irrigation schemes, and farmer acceptance due to skepticism, limited knowledge, and fear of unreliable water hindering adoption are highlighted. Future research suggestions include the following: (i) long-term measurement of water stress indices using infrared thermometers; (ii) seasonal suitability mapping using NDVI, GIS, and remote sensing; and (iii) application of smart sensors based on the Internet of Things (IoT) to address AWD challenges for precision water management in paddy fields with climate change.

**Keywords:** water management; paddy cultivation; paddy rhizosphere; food security; ecohydrological processes; climate change



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## 1. Introduction

Water stress is an increasingly common global challenge as increased uncertainty in climate due to climate change affects water availability in many regions, inhibiting livelihoods and environmental functions, especially those 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 hydrological processes are impacted by water regimes and are critical for irrigation management. While rice is a global staple crop essential for food security [4,5], the future of rice production is compromised by its greater susceptibility to drought stress than other cereal crops. Similarly, drought stress is predicted to increase with global warming in many areas, while irrigation supplies and costs may hinder paddy-rice production in some areas [6]. Likewise, extreme weather events, such as heavy rains often attributed to climate change, cause huge damage and losses to paddy-rice production. Changing rainfall patterns in Africa and Asia 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 paddy cultivation [8,9]. Increasing water shortages are affecting four billion people globally [10] and, by 2025, rice production is predicted to experience a water deficit of 20% [11]. Although rice contributes significantly to ensuring global food security, traditional continuous flooding (CF) practice in rice paddies requires more water, up to 2500 L for 1 kg of rice produced compared to other crops [12,13]. The CF practice is employed for 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 [14].

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 [13]. During drought conditions, appropriate irrigation management practices can lead to economic gains by maximizing rice productivity [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, alternate wetting and drying (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 while maintaining some weed control functions. AWD is currently the most widely used water-saving technology in rice production [19].

With 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 to bring the soil back to saturation [12–15]. Furthermore, AWD has been reported to reduce water inputs by 23% compared to traditional, continuously flooded systems [20]. A reduction of just 10% in water use for irrigated rice would save 150,000 million $m^3$, corresponding to about 25% of the total freshwater used globally for non-agricultural purposes [11]. However, rice is sensitive to drought stress, especially during the vegetative to flowering stage [14].

AWD technology is practiced mostly in Asia, employing triggering criteria for irrigation such as phreatic head or soil water potential (SWP) head [21]. For phreatic head measurements, a perforated pipe (observation well) is installed at 15–20 cm below to monitor the water level (WL). When the water level in the tube disappears, irrigation is applied [17]. The matric potential head-based criterion involves applying water when the matric potential in the rootzone reaches between −20 kPa and −70 kPa measured by the tensiometers, influenced by depth [21]. However, little is known about the following: (i) the relationship between SWP and WL criterion based on soil type and the spatial variability of hydraulic conductivity, which affects the efficiency of the irrigation application; (ii) the effects and interaction of the wetting and drying duration on hydrological conditions in the paddy-rice rhizosphere continuum; and (iii) the adoption of AWD by smallholder farmers and within large paddy irrigation schemes in developing regions, especially East Africa. In light of these limitations and to promote better understanding of AWD practice in the paddy-rice cultivation environment, this comprehensive review highlights the state-of-knowledge on the following: (i) the design and hydrological characteristics of paddy-rice environments; (ii) water management in paddy fields under AWD practice as a climate smart technique; and (iii) addresses specific questions related to the following:

(a) Whether puddling is essential in paddy-rice fields under AWD practice.

(b) Suitable paddy soil conditions and the implications of soil wetting and drying on soil hydrological conditions, crop yields, irrigation efficiency, and greenhouse gas (GHG) emissions in paddy-rice fields.
(c) Reasons farmers are skeptical in adopting AWD practice, particularly in the Sub-Saharan region—East Africa.

We then introduce details of the physical, hydrological, and water management aspects of paddy fields, followed by a discussion of AWD practice as a climate-smart water management practice, including its impacts on soil hydrological conditions, rice crop response, water use efficiency, and soil redox potential. The potential challenges, limitations, and obstacles in adopting AWD practice and its implications for soil carbon dynamics and GHG emission reduction are then introduced, along with future perspectives of improving AWD technology for adoption, particularly in East Africa.

## 2. Paddy-Rice Cultivation Environment

### 2.1. Attributes of Paddy-Rice Fields

The term "paddy" is derived from the Malay word "padi", meaning "rice plant", and originated from Proto-Austronesian. The concept of paddy fields is generally referred to as a paddy-rice farm, mainly in flooded conditions [22]. Paddy fields are designed with irrigation and drainage canals, complex schemes combining a myriad of technical, economic, agronomic, and social factors. The main objective is to create a layout that enhances water availability and equitable distribution among farmers. In addition, it involves intensive farmland consolidation to enhance regular fields in conjunction with straight segments of ditches and roads [23].

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 grown in bunded fields to produce one or more crops per year, and farmers usually maintain 5–10 cm of flooded water in the field [24]. Rainfed lowland rice is grown in bunded fields flooded with rainwater for at least part of the cropping season. In both cases, paddy fields are puddled before rice transplanting for rice crop establishment. In flood-prone areas, paddy fields periodically suffer from excess water due to uncontrolled flooding [24,25].

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 [26]. Field preparation involves bund shaping and puddling at the onset of the paddy season, with bunds shaped uniformly at a desired height and plastered with mud to retain water [26]. This helps to control weeds, keeps the field ponded during the rainy season, and reduces seepage loss. Similarly, irrigated paddy fields are also found in dry regions, requiring substantial water to maintain flooding. Evaporation of ponded water in these regions is high, as are seepage losses compared with paddy fields in wet regions.

Hydrological response in paddy fields largely depends on rainfall, irrigation management, and soil conditions (Figure 1). Farmers control water within paddy fields during rice cultivation [27]. Additionally, rainwater can be stored near paddy fields in ponds. Therefore, paddy fields can act as a buffer against flooding depending on storage capacity; this affects flood discharge due to changes in the water balance and associated water management of paddy fields [27]. 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 impacted by irrigation management and drainage canals. The planning and design of irrigation and drainage canals are essential for well-drained 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, unlined, or poorly constructed channels that lose water and deteriorate with time due to siltation and growth of weeds [28].

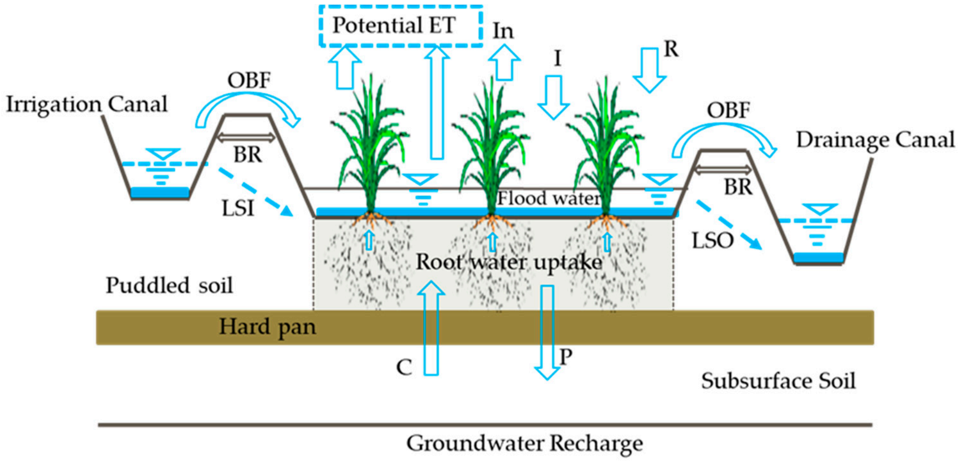


**Figure 1.** Schematic illustration of the conceptual water balance and water flow in a paddy field catchment. Legend: C: capillary rise; Potential ET: evaporation and transpiration; In: interception loss by canopy; I: irrigation; OBF: over-bund flow; P: percolation; R: rainfall; LSI: lateral seepage inflow from irrigation canal; LSO: lateral seepage outflow to drainage canal; BR: bund/ridge.

**Table 1.** Rice cultivation environment, climate, and major regions/countries. Source: [29,30].

| S/N | Major Categories | Sub-Categories | Climate Description | Major Regions/Countries |
|---|---|---|---|---|
| 1 | Irrigated | With conducive 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 Lowlands | RFS, suitable. RFS, drought-prone. RFS, drought- and submergence-prone. RFS, submergence-prone RFM deep, waterlogged. | Tropics | Cambodia, Northeast Thailand, eastern India, Indonesia, Myanmar, Nigeria |
| 3 | Upland | Suitable upland with LGS. Favorable upland with SGS. Unfavorable upland with LGS. Unfavorable upland with SGS. | Tropics | South Asia, Southeast Asia, Brazilian Cerrado, western Africa, East Africa, Uganda |
| 4 | Deep Water | Deep water. Very deep water. | Tropics | River deltas of South Asia and Southeast 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 |

Note: 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 is a vital aspect of paddy-rice water management systems that relates to rice crop water requirements in paddy fields as a measure of water lost from the system [31]. Water use efficiency is the ratio of grain yield produced to unit water transpired by plants during the cultivation season [32]. Transpiration is a key component of water balance in paddy fields, which also includes irrigation, rainfall, and evaporation from ponded water or soil surfaces, deep seepage losses, and percolation into the soil profile (Figure 1). The water balance of lowland rice fields has been widely studied [33,34]. Similarly, the water balance of irrigation regimes influences the hydrologic relations of plant shoots that control crop root water uptake [2,35]. Previous research found that morphological properties of roots of various crops have co-regulation pathways that interact with root–soil systems [36,37]. Therefore, drying and wetting conditions during AWD optimize the rhizosphere continuum and soil–root hydraulic properties that determine the root profile distribution in paddy soils. This has implications on rice yield due to the variable mechanical resistance of puddled and non-puddled soils [38].

A water balance helps to evaluate the efficiency of water use in paddy fields and groundwater recharge as follows [39]:

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

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

$$\mathrm{v} = \mathrm{IK} \quad (2)$$

where v is the velocity of percolation (cm/s); Ks is the hydraulic conductivity (cm/s); and I is the hydraulic gradient [40]. The hydraulic gradient (I) is the change in hydraulic head per unit distance of travel in the soil.

$$\mathrm{I} = \mathrm{H}/\mathrm{L} \quad (3)$$

Typically, L is the thickness of hardpan, 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.

### *2.3. Hydrological Properties of Paddy-Rice Fields*

#### 2.3.1. Puddling, Bunds, and Preferential Flow

Paddy field preparation is vital for creating favorable conditions for rice cultivation [41]. 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 [42]. However, it creates physical soil conditions detrimental for upland crops in rice-based cropping systems [43]. A typical soil profile in a paddy-rice field consists of three distinct layers, i.e., the top puddled layer, the middle-consolidated layer (also called the hard pan), and the bottom undisturbed soil [44]. The puddling index (PI) is an indicator of puddling quality of soils in paddy fields depending on farmers' tools, which include mechanical/tractor puddling implements such as cultivators, disc harrows, rotovators, and confine wheels. PI can be estimated using the following formula [41–45]:

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

where PI is the puddling index (%); Vs is the suspended soil volume in a measuring cylinder after 48 h (mL); and Vt is the total volume of sample collected (mL).

It is logical to question whether puddling is essential in paddy fields and, if so, in what conditions. The benefits of puddling in paddy fields have been reported [42,43] and include the following: (i) increased water holding capacity and yield due to increased soil microporosity and, importantly, decreased macroporosity; (ii) reduced air-filled pore volume by replacing air with water; and (iii) ease of transplanting, nutrient availability, and weed control. The following disadvantages associated with puddling have also been highlighted: firstly, the presence of a hardpan (compacted layer) and the development of a low hydraulic conductivity layer after puddling resist 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.

The hardpan has a high bulk density and low saturated hydraulic conductivity (Ks), making the layer more impervious to water than overlying soil layers [45]. Hydraulic properties of the hardpan dominantly control the water regime of puddled paddy fields, often creating an unsaturated zone below the hardpan [44,46]. Two other features of rice fields that affect the hydrologic regime are as follows: (1) the bund of raised soils surrounding the field that retains irrigation water; and (2) soil cracks that form preferential flow channels. Preferential flow in the vadose zone travels through localized pathways (macropores) by-passing the surrounding soil matrix, sometimes accounting for most of the flow in soils [47,48]. The hardpan formed while working paddies in saturated conditions compacts the soil, destroys aggregates, and acts as a barrier to water flow. Excavating through the hardpan can increase water loss from the field [39,44]. Smaller soil particles fill pore space and seal cracks and macropores as they deposit [45]. 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 [39–49].

#### 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 1). Percolation and lateral seepage represent the primary water losses from lowland paddy-rice fields [46,49–53]. Water percolation infiltrates the hardpan and progresses deeply, contributing to the recharge of aquifers and can potentially be reused for irrigation (Figure 1). Percolation rate after puddling depends on soil redox potential and water management [50,51]. In contrast, seepage moves laterally by pressure head differences between fields, thus decreasing the amount of water recharged into the aquifer (Figure 1). Therefore, lateral seepage must be separated from infiltration to estimate effective groundwater recharge from rice paddies [44,46,49].

Water flow through soils is controlled by several factors, including relatively static soil structure and composition. In 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 solution [54]. Generally, heavy textures (e.g., montmorillonite clay), high sodium levels in irrigation water, and high bulk densities favor effective puddling and low percolation [44,46,49]. Additionally, these dynamic processes are influenced by soil physical and hydraulic properties and water regimes [45]. Increased ponded water depths increase percolation due to the larger hydraulic gradient imposed [54]. Paddy-rice is a semi-aquatic plant, and percolation influences rice yields [53]. Rice cultivation is recommended in soils with minimum percolation rates, defined as Excellent, 1–2.5; Good, 2.5–5.0; Marginal, 5.0–10.0; and Unsuitable > 10.0 mm/day [55]. 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: [56].

| 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 |

Note: 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. [56].

| Treatment | Puddler Type for Treatment Description | Hydraulic Conductivity | | Percolation Loss | |
|---|---|---|---|---|---|
| | | Total cm/h | % 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 Crop Water Requirements*

Submerged paddy fields require much water due to percolation losses, and 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 securing economic benefits. Paddy crop water requirements are challenging; irrigation planning and design requirements for paddy fields must consider several paddy fields (units) with similar characteristics as a basic unit [28]. 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” [28]. 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 rice-paddy water consumption varies from 6 to 10 mm/day depending on agro-climatic conditions during crop cultivation [15]. Planning and optimal design of irrigation systems in paddy fields decrease crop water requirements. The estimated crop water requirement rate varies between 10 and 20 mm/day, although the actual water requirement rate may reach between 20 and 30 mm/day [57,58] depending on field conditions due to wetting and drying. However, in most tropical regions, the average potential evapotranspiration (ET) during the wet season varies between 4 and 5 mm/day, while in the dry season it is 8 to 10 mm/day. The seasonal water requirement for rice fields (rainfall plus irrigation) is up to 2–3 times that of other cereals [59,60]. Therefore, it is crucial to maintain the recommended crop requirement depending on crop stage, soil properties, climatic conditions, and irrigation systems. Crop water requirements influence soil water conditions and soil water deficits, affecting growth and yield due to reduced leaf surface area and photosynthetic rates via decreased stomatal conductance to $CO_2$ and photosynthetic metabolic potential [61].

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 in 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 [62]. In contrast, Bangladesh has three rice-growing stages, i.e., aus, aman, and boro. Aus is the pre-monsoon upland rice season 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 has the same schedule as aus, although transplanting occurs in July–August with harvesting in November. Boro is dry-season irrigated rice planted from December to early February and harvested between April and June [63]. Conversely, the suitable cropping calendar in East Africa (Kenya, Uganda, and Tanzania) is a combination of January–May and July–December, or February–June and August–January cultivations [64]. Mainly two rice varieties are cultivated in the world today, i.e., African rice (*Oryza glaberrima* Steud) and Asian rice (*Oryza sativa* L.). Additionally, *Oryza sativa* L. is subdivided into three groups, i.e., Indica, Japonica, and Javanica [65].

**Table 4.** Crop water requirement of each stage for rice paddy. Adapted from Ref. [66].

| 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. Paddy Cultivation and Climate Change*

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 [67,68]. Climate is denoted by either climate variability or climate change, i.e., short-term or long-term variations ranging from decades to millennia [69]. Although agriculture is likely the most vulnerable sector to climate change because of potential impacts on food production, climate effects are not evenly distributed [70]. Developing regions such as Africa are severely affected by climate change due to low adaptive capacities and slow recovery trajectories [71,72]. The impacts of climate change on rice production have been studied at regional and global scales [73–75].

Changes in precipitation and temperature directly affect crop productivity, but severe climatic events, such as droughts, are projected to have negative impacts on crop yield in Sub-Saharan Africa (SSA) and Asia, contributing to rice yield reductions [72,75,76]. Precipitation is extremely variable among the Mediterranean regions, with an average annual range between 100 and 2000 mm. Climate variability in most parts of Africa occurs on seasonal and decadal time scales, and the region experiences frequent droughts and floods [66,75]. As a result, these climate threats are major causes of hunger, malnutrition, poverty, and obstacles to social and economic development [75].

Rice is a staple food for more than 3 billion people globally, and consumptive demand has surpassed production since 2000 [77]. By 2010, rice production was 696 million tons, with 90% (Table 5) coming from Asia [78]. Conversely, rice production is equally a contributor to and a target of climate change. Climate events such as droughts, floods, saltwater incursions, 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 [75,79]. Such damaging events are projected to exacerbate rice production value chains in the future [79], 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 [80].

Notable increases and decreases in rice production have occurred in various regions (Table 5). An overall global increase in rice production up to 10.52% is evident, with a few Asian countries, including the Philippines, Bangladesh, and Indonesia, experiencing slight increases, while India had a significant increase up to 10.45% from 2019 to 2023. Likewise, several countries, including China, Vietnam, Thailand, Myanmar, Cambodia, Nepal, Japan, Nigeria, and South Korea, have seen decreasing trends in rice production up to 1.71% (Table 5), negatively impacting food security in developing regions, particularly SSA and East African nations (Table 5). These declines in rice-production in major rice-producing nations appear to be accelerated by climate dynamics, including rainfall variability and increasing droughts [66,75,79].

Studies of climate trends and drought indices in the Mun River basin, Thailand, noted declining rainfed rice yields due to low altitudes [81] and water shortages. Additionally, 90% of rice cultivation in Mun River basin is affected by climate variability and change [81]. Vietnam is one of the leading rice-producing regions and the world's largest exporter of rice, growing 90% of the exported rice in the Mekong River Delta [82,83]. Rice production in this region is susceptible to reduced yields due to low-lying topography, which is vulnerable to sea level rise, saltwater intrusion, and storm surges [82]. Likewise, rising temperatures may detrimentally impact rice production in the region, which contributes 65% of farm income [84].

Similar evidence of negative climate impacts on rice production, based on observations or projections, is noted in SSA. Widespread reductions in rice yields have been across SSA, including in Tanzania, Burkina Faso, and West Africa [79,85–87]. Reductions in both rice yield and grain quality were found in Nigeria, declining crop productivity occurred in South Africa, and substantial crop and income losses occurred among small-holder farmers in Madagascar [88–91]. 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 [92].

Studies indicate that global warming will have considerable impacts on crop productivity and quality [93–96]. Research in Japan shows that high temperatures during the growing period drastically degrade rice grain quality [96], a serious issue in Japanese rice production due to inducing chalky rice grains. The high chalky rice grain decreases grain grade, lowers farm income, and causes large economic losses [96]. Therefore, strengthening climate adaptation and mitigation measures, such as implementing AWD practices, should be emphasized to improve rice yields and reduce GHG emissions from paddy fields.

**Table 5.** The top 15 rice-producing countries in the world (milled production, 1000 metric tons) with corresponding changes in rice production for 5 years using 2018 as the base year. Data source: [97].

| | Milled Rice Production (1000 Metric Tons) | | | | | | Changes in Rice Production (%Age with 2018/19 as Base Year) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country** | **2018/19** | **2019/20** | **2020/21** | **2021/22** | **2022/23** | **2022/23** | **2019/20** | **2020/21** | **2021/22** | **2022/23** | **2022/23** |
| China | 148,490 | 146,730 | 148,300 | 148,990 | 145,946 | 145,946 | −1.185 | −0.128 | 0.337 | −1.713 | −1.713 |
| India | 116,484 | 118,870 | 124,368 | 129,471 | 132,000 | 132,000 | 1.607 | 5.309 | 8.746 | 10.449 | 10.449 |
| Bangladesh | 34,909 | 35,850 | 34,600 | 35,850 | 35,850 | 36,350 | 0.634 | −0.208 | 0.634 | 0.634 | 0.970 |
| Indonesia | 34,200 | 34,700 | 34,500 | 34,400 | 34,600 | 34,000 | 0.337 | 0.202 | 0.135 | 0.269 | −0.135 |
| Vietnam | 27,344 | 27,100 | 27,381 | 26,769 | 27,000 | 27,000 | −0.164 | 0.025 | −0.387 | −0.232 | −0.232 |
| Thailand | 20,340 | 17,655 | 18,863 | 19,878 | 20,200 | 20,200 | −1.808 | −0.995 | −0.311 | -0.094 | -0.094 |
| Burma | 13,200 | 12,650 | 12,600 | 12,352 | 12,500 | 12,500 | −0.370 | −0.404 | −0.571 | −0.471 | −0.471 |
| Philippines | 11,732 | 11,927 | 12,416 | 12,540 | 12,411 | 12,411 | 0.131 | 0.461 | 0.544 | 0.457 | 0.457 |
| Japan | 7657 | 7611 | 7570 | 7636 | 7450 | 7480 | −0.031 | −0.059 | −0.014 | −0.139 | −0.119 |
| Brazil | 7140 | 7602 | 8001 | 7337 | 6936 | 6800 | 0.311 | 0.580 | 0.133 | −0.137 | −0.229 |
| Pakistan | 7202 | 7206 | 8420 | 9323 | 6600 | 6600 | 0.003 | 0.820 | 1.428 | −0.405 | −0.405 |
| Cambodia | 5742 | 5740 | 5739 | 5771 | 5933 | 5933 | −0.001 | −0.002 | 0.020 | 0.129 | 0.129 |
| Nigeria | 5294 | 5314 | 5148 | 5255 | 5040 | 5040 | 0.013 | −0.098 | −0.026 | −0.171 | −0.171 |
| Korea South | 3868 | 3744 | 3507 | 3882 | 3764 | 3764 | −0.084 | −0.243 | 0.009 | −0.070 | −0.070 |
| Nepal | 3736 | 3697 | 3744 | 3417 | 3654 | 3654 | −0.026 | 0.005 | −0.215 | −0.055 | −0.055 |
| Others | 43,780 | 46,667 | 46,939 | 44,898 | 44,854 | 44,649 | 1.944 | 2.127 | 0.753 | 0.723 | 0.585 |
| Subtotal | 491,118 | 493,063 | 502,096 | 507,769 | 504,738 | 504,327 | 1.310 | 7.393 | 11.214 | 9.172 | 8.896 |
| World Total | 498,225 | 498,940 | 509,320 | 513,852 | 509,830 | 509,419 | 0.482 | 7.472 | 10.524 | 7.815 | 7.539 |

Note: Negative values imply a decrease in rice production with reference to the base year 2018/19 or otherwise.

### 2.6. Water Management Strategies in Paddy-Rice Fields

Developing and promoting appropriate water management technologies to increase water efficiency in paddy fields without affecting yields is desirable and requires a holistic approach, including integrated crop, soil, and water management [24]. Water management in paddy fields starts with the design, distribution, application, use, and removal of excess water from fields with the intent to maximize crop production and improve water use efficiency and labor productivity [67].

Water use and management techniques in irrigated paddy fields are practiced using the rice intensification system (SRI). Caution must be taken in promoting such techniques as "one-size-fits-all" solutions due to regional differences in paddy environments, and local and site-specific adaptations must be considered. SRI is believed to have originated in Madagascar and includes a suite of recommendations differing from conventional methods, including crop establishment-transplanting of single seedlings, transplanting in the square, irrigation management, weed control, and fertilizer application [68]. SRI techniques are based on close field observations of the biological characteristics of rice plants while manipulating the natural genetic potential [69]. The promotion of SRI assumes 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 [68,70].

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 not been well investigated [70]. Rice production is strongly affected by water availability, and yield increase is a function of increases in transpiration and reductions in other water balance factors, i.e., evaporation, seepage, and percolation [98,99]. Water conservation and high crop water productivity can be realized through SRI practices since they include good agronomic practices that increase the harvest index, resulting in more grains per unit water transpired by the crop [24,100].

Similarly, water-saving techniques are essential to help farmers cope with water scarcity during climate change [101]; these include the following: (i) direct seeding; (ii) saturated soil culture; and (iii) AWD practice [100]. 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 labor [102]. Direct seeding involves broadcast sowing/row seeding of dry rice seeds on dry (or moist) fields and has contributed to more efficient water use in Malaysia [103]. Classifications of directly seeded rice systems are shown in Table 6.

**Table 6.** Classification of directly seeded rice systems. Adapted from Refs. [102,104].

| 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 leveling and in areas with red rice problems |

Saturated soil culture (SSC) is a water management technique where soil is usually kept near saturation by daily applications of 1 cm of irrigated water after ponded water disappears [24]. 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 of 5–50%) compared to continuously flooded rice fields, with only a 6% (non-significant) reduction in yield [20]. Addressing climate dynamics and concerns to protect agroecological and socioeconomic functions of wetlands requires policies that promote climate-smart water management techniques, particularly AWD practice.

## 3. Defining AWD Practice in Rice-Paddy Fields

In AWD, rice paddies are intermittently irrigated, except during the rooting, panicle formation, and flowering stages, reducing water use by 15–40% [105]. Water application strategies in AWD practice are classified as follows: (a) phreatic head-based or (b) soil water potential 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 2) [17]. The AWD is classified as follows: (1) safe AWD, when soil water potential (SWP) in the paddy-rice rhizosphere is allowed to drop below −20 kPa (SWP $\geq$ −20 kPa) or WL is allowed to drop $\leq$15 cm deep inside the water tube; (2) mild AWD, when SWP in the rhizosphere is permitted to drop to −45 kPa (SWP $\leq$ −45 kPa); and (3) severe AWD, when SWP in the rhizosphere reaches −70 kPa [21,24].


**Figure 2.** 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 Refs. [101,105,106].

### 3.1. AWD Recommendations

The most practical approach to AWD irrigation by farmers in the paddy field is using a field water tube ('observation pipe') [105]. The perforated observation tube has holes (0.5 cm diameter) drilled at 2 cm apart throughout the buried length of the tube (Figure 2). This simple tool can be made from plastic, bamboo, or any cheap material and is installed in paddy fields to a depth of up to 20 cm. Observation tubes are used to monitor water depth in the field using a metric ruler. Diminished water depth is mostly due to evapotranspiration, deep percolation, and lateral seepage losses [107]. 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., not in a high or low location) [106]. 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 [105,106]. AWD can be introduced 1–2 weeks after transplanting or when crop height is about 10 cm, although when many weeds exist, AWD should be delayed for 2–3 weeks to suppress weeds with ponded water [101]. Fertilizer application, particularly nitrogen, is recommended on dry soil before irrigation, similar to traditional flooding [106]. Likewise, care should be taken during the installation and maintenance of the tube, including removing soil from inside the tube (siltation), covering the holes and lower well of the tube with fine plastic mesh, and ensuring that 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) [106]. Siltation is a problem due to clogging of perforations and has been reported to reduce the performance of AWD using observation water tubes [108]. Relatively narrower water tubes are mostly affected by siltation. Paddy sediment and turbid water in fields where rice is transplanted in puddled conditions may pass into water tubes, and after settling, siltation occurs [109]. 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 [110]. 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 at 5-day intervals are suitable for AWD, although 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 [106].

### *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 [14]. 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 [12]. 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 [111]. 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 indicates that crop height after 40 days and growth after direct seeding were similar for both control and safe AWD regimes (i.e., when WL dropped to 5, 10, and 15 cm depth in observation tubes) [14].

Furthermore, if water declines to 15 cm in observation tubes, the soil is still near saturation and water is available for rice growth (Figure 3). Therefore, irrigation can be applied when the water level in the paddy-rice field drops to 10–20 cm below the soil surface without inducing significant yield reduction [112]. 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 2–8 days before re-irrigation [20]. Such scenarios may vary depending on soil type, structure, and hydrological properties. Yields in acidic soils with AWD practice were higher than in soils with a pH $\geq 7$ [12]. These differences can be due to the high percentage of exchangeable sodium (Na), which causes dispersion in alkaline soils [113]. 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 [114]. 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 [113]. When AWD is practiced throughout the season, yield reductions were observed compared to when practiced in either the vegetative or reproductive stages [12].

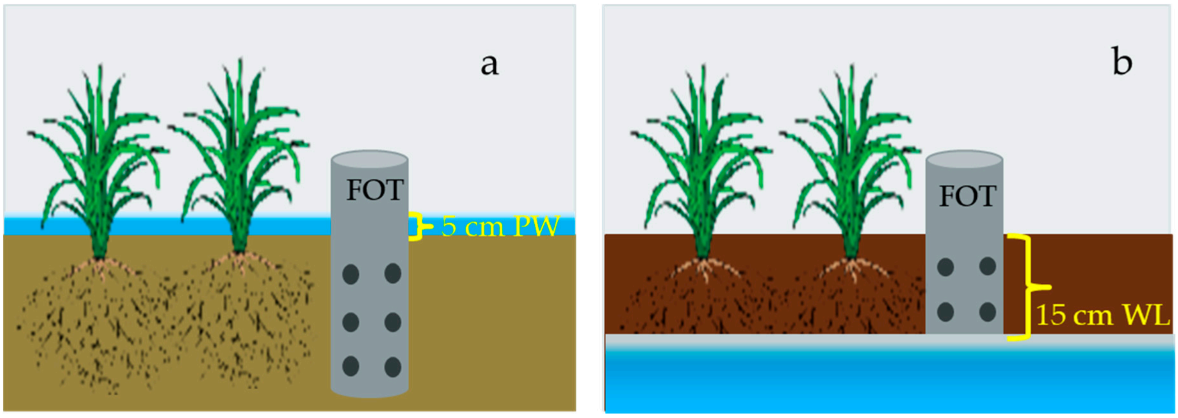


**Figure 3.** Illustration of AWD conditions: (**a**) soil wetting during irrigation; (**b**) soil drying after a number of days. Legend: FOT: field observation tube or well; WL: water level/water table below soil surface; PW: ponded water after irrigation. When WL is allowed to drop $\leq$15 cm in depth, the site is considered in a safe AWD condition.

Not all the rice crop tillers develop to mature tillers; some become dormant when young and die later depending on environmental and nutrient conditions [115], thus affecting yield. Rate of crop recovery due to reapplication of water depends on soil conditions, such as soil water, pre-drought intensity, and duration of soil drying [116]. In contrast, short-duration soil drying does not affect crop growth, rice tillering, or general yields [12].

### 3.2.2. Water Use Efficiency and Productivity

Several studies on AWD practice have shown increased crop productivity when water inputs were reduced. Various field experiments comparing AWD to continuous flooding have been conducted in Asia, including China [117,118], India [119], and the Philippines [120], all confirming the high water-saving potential of AWD.

AWD irrigation reduces water use on average by 26% compared to CF, although harsh AWD conditions reduce water use by 33% with corresponding yield reductions [12]. 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 [121]. Nevertheless, AWD technology significantly reduces irrigation frequency compared to typical rice paddy practices, lowering irrigation water consumption as well as fuel (30 L/ha during one growing season) [122]. The effect of AWD practice on yield and water productivity is summarized in Table 7.

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

| S/N | Component | Details | Authors |
| --- | --- | --- | --- |
| 1 | Wp, WUE, Water Saving | Higher Wp (1.74 g $L^{-1}$) in AWD compared to CF (1.23 g $L^{-1}$) | [123] |
| | | WUE (85.55 kg $ha^{-1}$ cm) in AWD with quite a large water saving (15 cm) compared to continuous submergence | [124] |
| | | Water saving of 15–20% with AWD without a significant impact on yield | [117] |
| | | 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 | [12,13] |
| | | Water application once in 7 days consumed the lowest amount of water (80.30 cm) and saved 41% water | [125] |
| | | Water savings in AWD by 40–70%, 20–50% compared to CF | [126] |
| | | 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 $m^{-3}$) | [107] |
| | | AWD improves WUE and yields with 5, 7, and 10 days of irrigation interval | [109,127] |
| 2 | Yield components | 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 | [107] |
| | | 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 | [128] |
| | | 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 | [129] |
| | | Water application intervals of 5 and 8 days with CF produced statically the same grain yield. (7342, 7079, and 7159 kg $ha^{-1}$, respectively) | [130] |
| | | Grain yield was higher in saturated condition (7.6 t $ha^{-1}$) compared to CF (7.1 t $ha^{-1}$) in Malaysia | [131] |
| | | Application of safe AWD levels did not result in loss of rice yield | [132] |
| | | Increases rice yield by 10% with AWD | [133] |

Note: 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 [134]. Paddy soil typically consists of at least 35% clay, thus clay-textured according to the USDA [135]. Formation of cracks in heavy clay soils affects agricultural water and crop production, a characteristic feature of paddy soils with AWD practice [136]. Alternatively, swelling and shrinkage in paddy soils are driven by decreased soil moisture and clay content that differ spatially [134,137]. 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 clay microstructures [48,136]. These cracks are less conspicuous with continuous flooding [138,139]. Hydrological properties of paddy soils are significantly altered by cracks. Wide and deep cracks transfer more water quickly from the soil surface to subsurface soil layers [140]. The amount, connectivity, and extent of cracks control the preferential routing of water losses via percolation and seepage [141]. Therefore, cracks significantly affect the accuracy of the field measurement of ponded water after irrigation.

Preferential flow pathways caused by cracks facilitate water infiltration [142] and increase the risk of groundwater pollution via fertilizer, pesticide, and herbicide percolation [143]. These pathways allow water to bypass the soil matrix [144]. Evidence from field research indicates that 70–85% of water flux may be attributed to preferential flow. This creates challenges for predicting water and solute movement in field conditions [144,145]. Cracks formed during soil drying increase hydraulic conductivity; during wetting, crack closure reduces the infiltration rate [143]. Few research studies have been conducted to better understand the changes in the hydraulic properties, including hydraulic conductivity, infiltration, and anisotropy caused by cracking, cyclic swelling under drying, and wetting conditions of AWD practice within the paddy soil rhizosphere continuum at different rice cultivation and growth stages. Water infiltration rates in paddy soils with cracks in China showed that cracks and subsequent swelling increase and reduce infiltration rates, respectively [143]. Further research is required to assess and understand the interactions of these phenomena and quantify the possible range of infiltration and changes in hydraulic conductivities in the paddy rhizosphere during different rice cultivation stages with AWD practice.

### 3.2.4. Redox Potential with AWD Practice

Although water savings can be achieved with AWD, savings can be improved by modifying the rooting behavior of rice cultivars [146]. AWD has potential to alter macro- and micronutrient availability and uptake. Aerobic growth favors enhanced selenium accumulation in rice [147], while decreasing arsenic uptake [148,149]. Arsenic accumulation increases in anaerobic soils because inorganic arsenic is present as arsenite (as opposed to arsenate in aerobic soils), the former of which is more readily taken up by plant roots [150].

The AWD regime affects soil redox potential since metals in pore water and the readily exchangeable solid phase vary significantly. Research on these trends at relevant temporal and spatial scales is limited [146]. Additionally, redox potential is a challenging factor with water regimes, although high redox potential with AWD practice can occur at the booting to grain formation stage of rice paddy [13]. Soil redox potential (Eh) influences net $NH_{4+}$ (de)fixation, which refers to both fixation and de-fixation of $NH_4$ in paddy soils by nitrogen (N) fertilizer application. All structural $Fe_{3+}$ in phyllosilicates is biogenically reduced with a consequent increase in the negative charge of clay minerals, which creates strong action between $NH_4$ cations and clay minerals at low Eh [151,152]. The effect of Eh on $NH_{4+}$ (de)fixation is also indirect via its control on the occurrence of external N transformation processes, including mineralization and (de)nitrification, that could affect exchangeable $NH_{4+}$ concentrations and the dynamic balance with fixed $NH_4$ [153].

## 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 [154]. 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 [155]. Similarly, unreliable water and energy supplies are potential obstacles for adopting AWD because it requires well-tuned irrigation intervals and management measures. The technology also requires more time for field inspection and manual measurements of WL. 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.

Rice cultivars with shallow roots will have a greater 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 uptake of phosphorous [146,156]. Cadmium (Cd) accumulation in grains is debatable for paddy-rice grown in more aerobic conditions [157]. However, some research has shown that mild and severe paddy soil drying can reduce grain accumulation of Cd [134]. Thus, in promoting and adopting AWD programs, reducing Cd accumulation in rice grains should be considered [158].

Optimizing AWD irrigation requires addressing a question: "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 need to be evaluated since one observation tube per paddy may not fully represent WL variation in the paddy field. Evaluation of WL monitoring design and integration into large irrigation schemes necessitates solving the first question due to the impact of AWD on hydrological properties in paddy soils. However, field measurements and quantification of root growth in the soil are difficult, time-consuming, and labor-intensive [159]. Although application of digital tools combining RSAvis3D and RSAtrace3D models that use bottom-up and top-down approaches, respectively, can be effective for measuring root system architecture (RSA) [160]. Adopting a bottom-up approach using RSAvis3 will enhance rapid visualization of the root system since it avoids human intervention [161]. Such technologies are related to rice production and improve water management in a changing climate. Therefore, governments in SSA and other developing regions should craft workable policies that enhance adoption of appropriate technologies in a changing climate that affects paddy-rice farming.

### *4.1. AWD Practice as Climate Adaptation and Mitigation Strategy*

Efforts to increase rice and water productivity while developing adaptive and mitigation measures for paddy cultivation systems to climate dynamics is a growing topic in climate-smart agriculture (CSA). Specific indicators focusing on such 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 requires metrics that concurrently amalgamate all three topics (i.e., productivity, adaptation, and mitigation) while comparing various water management strategies and offering different benefits, trade-offs, or synergies from the three points [162].

Water resources and irrigation development for paddy-rice cultivation require significant transformations, especially in the East African region of SSA, to meet food security challenges and climate change. Recently, increased human activities are influencing climate, where water and GHG emissions are two key factors affecting climate [122]. AWD technology has been proven to be a GHG mitigation measure, reducing $CH_4$ emissions up to 50%. $CH_4$ is produced anaerobically by methanogenic bacteria that thrive in paddy-rice fields (Figure 4). Hence, traditional flooding in paddy-rice fields is the largest source of $CH_4$ emissions, the second largest anthropogenic source after ruminant livestock [122].

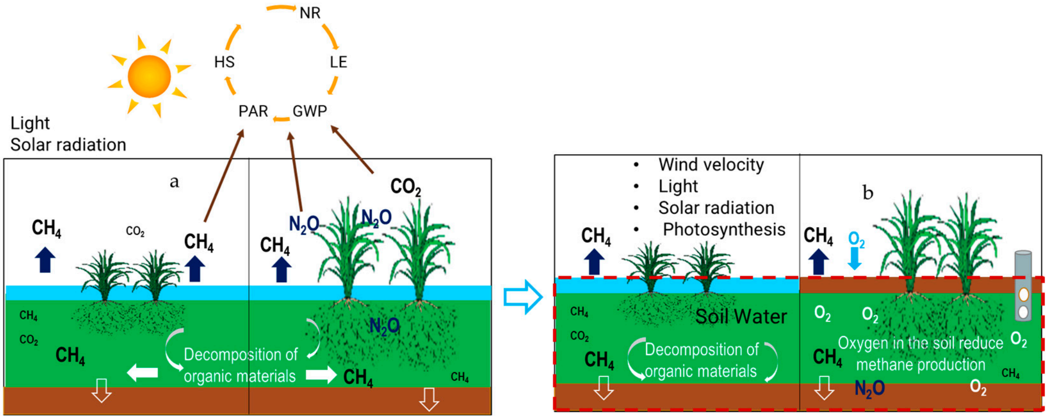


**Figure 4.** Conceptual illustration of changes in SOC and GHG interactions in paddy fields under (**a**) anaerobic respiration in absence of oxygen under traditional flooding conditions (CF) and (**b**) aerobic respiration in presence of oxygen due to soil drying conditions under AWD irrigation. Legend: GWP: global warming potential; PAR: photosynthetically active radiation; HS: sensible heat; NR: net radiation; LE: latent heat.

In contrast, AWD influences the production of nitrous oxide ($N_2O$), another potent GHG gas. The $N_2O$ has a global warming potential (GWP) of 298, implying that it is 298 times more effective in trapping heat in the Earth's atmosphere than $CO_2$, while $CH_4$ has a GWP of 25 [163]. $N_2O$ emissions tend to increase due to increased nitrification and denitrification activities when the soil conditions constantly change between anaerobic and aerobic conditions and related changes in soil redox potential. However, data on $N_2O$ emissions under different water management regimes are scarce [122].

### *4.2. Methane GHG and Carbon Equivalent Estimation in Paddy-Rice Field*

There are several approaches to estimate GHG emissions, including methane in paddy fields. $CH_4$ emissions from paddy fields can be estimated as follows [164]:

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

where:

$CH_4$Rice = Amount of $CH_4$ emissions from rice cultivation (Gg $CH_4$ $yr^{-1}$).
A = Annual harvested area (ha $yr^{-1}$) or ($m^2$/yr).
t = Cultivation period of rice (day).
$EF_i$ = Emission factor for harvested area (kg $CH_4$/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 $CH_4$ 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 $EF_i$ (Equation (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 $CH_4$ 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 (flood regime) or fields under water with AWD practice. This occurs either for 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 represent water regimes modified by other factors like organic inputs, soil texture, and fertilization regimes for each condition represented by index i. When more factors are identified, more categories need to be included. 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 $CO_2$ equivalent can be estimated as follows:

$$CO_2e = GHG \times GWP \tag{7}$$

where:

$CO_2e$ = Equivalent carbon dioxide.
GHG = Greenhouse gas.
GWP = Global warming potential (metric tons).

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

The campaign and policies for expansion of rice production to meet food 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 [165]. Soil organic matter is crucial for both plant and $CH_4$ productivity (Figure 4) and quantifying the carbon balance helps constrain estimates of changes in organic matter.

The sustainability of rice yields depends on soil fertility, which is related to soil organic carbon (SOC) [166]. 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. Loss of SOC due to changes in water management contributes to yield reductions [167], thus 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 [168]. Likewise, a comprehensive accounting is needed to place GHG reduction and carbon dynamics into a broader context, thus balancing reductions in $CH_4$ emissions with increases in $CO_2$ production [165].

## 5. Suggestions and Research Directions

In this comprehensive review, we complied and discussed the following: (i) information on paddy-rice cultivation systems and water management strategies; (ii) how puddling influences water flow and management; and (iii) implications of soil wetting and drying conditions of AWD practice on soil hydrological conditions and soil water balance components in paddy-rice fields. Additionally, the impacts of AWD practice on crop yields, water use efficiency, and GHG emission mitigation were discussed. Similarly, the challenges and limitations for adopting AWD practice, as well as workable policies for promotion of the technology in East Africa, were examined. Finally, this review provides a guide to better understand paddy-rice environments and hydrological conditions for improving the design of AWD technology and to provide technical support for policymakers. Here we offer suggestions for future research directions.

AWD technology is applied either by monitoring WL or SWP. Detailed classification of AWD based on SWP has not been fully addressed in recommendations from the International Rice Research Institute (IRRI), necessitating 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 may be difficult for farmers to implement AWD by SWP since it requires measurements by smart sensors which are costly, and lack of technical knowledge and training. These issues require further attention.

Applying AWD by monitoring WL in observation tubes is widely accepted and easily adopted. However, the corresponding SWP may not match the WL criterion and the efficiency of WL measurements is affected by soil type, variations in paddy field slopes, spatial variability of hydraulic conductivity with depth, position in paddy fields, climatic conditions, and practical knowledge, requiring further field investigation. Similarly, automation of AWD practice using smart sensors based on the Internet of Things (IoT) could improve water use efficiency based on real-time alerts using field soil, crop, and weather data [169].

Seasonal mapping of NDVI of paddy fields, including changes in hydrological properties 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 the 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 climate 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 fields [170]. The climate suitability criteria for AWD in the Philippines indicate that the technology is highly reliable during dry-season rice cultivation. 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 [170]. 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 [171]. Long-term evaluation of drought stress index in rice fields and its effect on yields, soils, and root architecture of different paddy-rice cultivars is vital.

Assessing crop water stress index using an infrared thermometer to measure canopy temperature should be considered to enable continuous monitoring of crop water status by integrating both soil water status and climatic conditions for accurate water management. This approach is non-destructive, scalable from plant to field conditions, and can be implemented at larger spatial or temporal scales compared to other techniques (i.e., soil moisture sensors) [172–175].

Additionally, coupled climate and rice crop (*Oryza sativa*) models with artificial intelligence—machine learning algorithms for paddy-rice fields—are beneficial since rice feeds more people compared to other crops [25]. Agricultural water uses and management relies on various factors, i.e., 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 those topics is relatively scarce and is still at an early development stage [176].

Finally, designing an integrated approach for adoption and promotion of AWD technology to improve water management, especially in East Africa, requires the following: (1) increased funding for research, pilot demonstrations, and technology transfer of the AWD practice; (2) feasibility analysis of paddy-rice fields, effects on groundwater resources, and integration in planning of large paddy irrigation schemes by engineers, administrators, and managers to implement the technology; (3) selection of champion farmers as visible examples to promote farmer-to-farmer learning approaches; and (4) partnerships with stakeholders and AWD practitioners to facilitate information dissemination [177]. Improving emission and carbon credit trading by designing AWD technology as a climate-smart practice based on the clean development mechanism (CDM) of the Kyoto Protocol of 1997 will accelerate adoption of this practice. This offers win–win options for climate mitigation, contributing to achieving sustainable development as well as economic benefit to farmers [122].

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## References

1. Misr, K.A. Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ.* **2014**, *3*, 153–165. [CrossRef]
2. Sidle, R.C.; Khan, A.A.; Caiserman, A.; Qadamov, A.; Khojazoda, Z. Food security in high mountains of Central Asia: A broader perspective. *BioScience* **2023**, *73*, 347–363. [CrossRef]
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*, 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. [CrossRef]
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 Agric.* **2020**, *2*, 36–40. [CrossRef]
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. 2008. Available online: https://www.thenewhumanitarian.org/news/2008/04/01-1 (accessed on 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*, 9971–9975. [CrossRef]
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.; et al. Comprehensive Impacts of Climate Change on Rice Production and Adaptive Strategies in China. *Front. Microbiol.* **2022**, *13*, 926059. [CrossRef]
10. Mekonnen, M.M.; Hoekstra, A.Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2016**, *2*, e1500323. [CrossRef] [PubMed]
11. Tuong, T.P.; Bouman, B.A. Rice production in water–scarce environments. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*; Kijne, J.W., Barker, R., Molden, D., Eds.; CABI Publishing: Wallingford, UK, 2003; pp. 53–67.
12. 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. [CrossRef]
13. Bwire, D.; Saito, H. Influence of Alternate Wetting and Drying Irrigation Conditions on Soil Redox Potential, Water productivity and Agronomic Performance of Paddy Rice. In *Proceedings of the 72nd Meeting of Japanese Society of Irrigation, Drainage and Rural Engineering, Kanto Region, 2021*; Book of Abstract; pp. 16–20. Available online: https://www.researchgate.net/profile/Bwire-Denis/publication/366481833_Influence_of_Alternate_Wetting_and_Drying_Irrigation_Conditions_on_Soil_Redox_Potential_Water_productivity_and_Agronomic_Performance_of_Paddy_Rice/links/63a315e6a252ce252f512028/Influence-of-Alternate-Wetting-and-Drying-Irrigation-Conditions-on-Soil-Redox-Potential-Water-productivity-and-Agronomic-Performance-of-Paddy-Rice.pdf (accessed on 4 June 2024).
14. 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*, 3368. [CrossRef]
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. *Paddy Water Environ.* **2022**, *20*, 1–21. [CrossRef]
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 Manag.* **2007**, *88*, 1–13. [CrossRef]
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. [CrossRef]
18. Mao, Z. Water Efficient Irrigation and Environmentally Sustainable Irrigated Rice Production in China, International Commission on Irrigation and Drainage. 2001. Available online: https://www.icid.org/wat_mao.pdf (accessed on 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. *Agric. Water Manag.* **2020**, *241*, 106363. [CrossRef]
20. Bouman, B.A.M.; Tuong, T.P. Field water management to save water and increase its productivity in irrigated lowland rice. *Agric. Water Manag.* **2001**, *49*, 11–30. [CrossRef]
21. 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 Water Environ.* **2019**, *18*, 73–85. [CrossRef]
22. Watanabe, T. Paddy Fields as Artificial and Temporal Wetland, Book Chapter 9, Irrigations in Ecosystems. Available online: https://www.intechopen.com/chapters/63233 (accessed on 20 April 2023). [CrossRef]
23. 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 Manag.* **1996**, *30*, 185–199. [CrossRef]
24. 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; 54p.
25. 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.
26. Ranjan, R.; Pranav, P.K. Cost analysis of manual bund shaping in paddy fields: Economical and physiological. *Res. Agric. Eng.* **2021**, *67*, 181–189. [CrossRef]
27. Kim, S.J.; Park, G.A.; Kwon, H.J. Evaluation of Paddy Water Storage Dynamics during Flood Period in South Korea. *KSCE J. Civil. Eng.* **2007**, *17*, 269–276. [CrossRef]
28. Sayed, M.B.; Senge, M. The Impact of Various Environmental Changes Surrounding Paddy Field on Its Water Demand in Japan. *Rev. Agric. Sci.* **2020**, *8*, 199–215.
29. 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. *Arch. Agric. Environ. Sci.* **2019**, *4*, 83–87. [CrossRef]
30. Khus, G.S. *Terminology for Rice Growing Environments*; International rice Research Institute (IRRI): Los Banos, Philippines, 1984. Available online: https://pdf.usaid.gov/pdf_docs/PNAAR582.pdf (accessed on 10 April 2023).
31. Huanga, H.C.; Liua, C.W.; Chen, S.; Chen, J.S. Analysis of percolation and seepage through paddy bunds. *J. Hydrol.* **2003**, *284*, 13–25. [CrossRef]
32. Hatfield, L.H.; Dold, C. Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Front. Plant Sci.* **2019**, *10*, 103. [CrossRef]
33. 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. [CrossRef]
34. 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. [CrossRef]
35. 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. [CrossRef]
36. 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*, e0180713. [CrossRef]
37. 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. [CrossRef]
38. Kato, Y.; Okami, M. Root growth dynamics and stomatal behavior of rice (*Oryza sativa* L.) grown under aerobic and flooded conditions. *Field Crops Res.* **2010**, *117*, 9–17. [CrossRef]
39. Chen, S.K.; Liu, C.W.; Huang, H.C. Analysis of water movement in paddy rice fields (II) simulation studies. *J. Hydrol.* **2002**, *268*, 259–271. [CrossRef]
40. Yukawa, K. The fluctuation of irrigation requirement for paddy fields. In *Proceedings of the International Workhop*; Asian Institute of Technology: Bangkok, Thailand, 1992; pp. 32–42.
41. Prasanthkumar, K.; Saravanakumar, M.; Gunasekar, J.J. Water Management through Puddling Techniques. *J. Krishi Vigyan* **2019**, *8*, 297–300. [CrossRef]
42. 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.
43. 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.
44. 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. [CrossRef]
45. Patil, M.D.; Das, B.S. Assessing the effect of puddling on preferential flow processes through under bund area of lowland rice field. *Soil Tillage Res.* **2013**, *134*, 61–71. [CrossRef]
46. Wopereis, M.C.S.; Bouman, B.A.M.; 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 Manag.* **1994**, *26*, 277–289. [CrossRef]
47. Beven, K.J.; Germann, P. Macropores and water flow in soils revisited. *Water Resour. Res.* **2013**, *49*, 3071–3092. [CrossRef]
48. 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. [CrossRef]

49. 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. [CrossRef]
50. 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. [CrossRef]
51. Adachi, K. Effect of puddling on rice physical: Softness of puddled soil on percolation. In *Proceedings of the International Workshop of Soil and Water Engineering for Paddy Field Management*; Asian Institute of Technology: Bangkok, Thailand, 1992; pp. 220–231.
52. Xu, B.; Shao, D.; Fang, L.; Yang, X.; Chen, S.; Gu, W. Modelling percolation and lateral seepage in a paddy field-bund landscap with a shallow groundwater table. *Agric. Water Manag.* **2019**, *214*, 87–96. [CrossRef]
53. Sharma, P.K.; De Datta, S.K. Response of wetland rice to percolation under tropical conditions. In *Proceedings of the International Workshop, Soil and Water Engineering for PADDY Field Management*; Asian Institute of Technology: Bangkok, Thailand, 1992; pp. 109–117.
54. 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.
55. 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.
56. Salokhe, V.M.; Shirin, A.K.M. Effect of puddling on soil properties: A review. In *Proceedings of the International Workshop*; Asian Institute of Technology: Bangkok, Thailand, 1992; pp. 276–285.
57. Mizutani, M. Positive studies on the formation of surplus water requirement (Part 3)—On the variable characteristic of net water requirement. *Bull. Fac. Agric. Mie Univ.* **1980**, *61*, 65–96.
58. Fujii, D.; Yamamoto, T.; Inoue, T.; Nagasawa, T. *Change in Water Use by Irrigation System from Open Channel to Pipeline*; Abstract; Japanese Society of Irrigation, Drainage and Rural Engineering (JSIDRE): Tokyo, Japan, 2009; pp. 436–437.
59. Tuong, T.P. Technologies for efficient utilization of water in rice production. In Proceedings of the Advances in Rice Science of the International Rice Science Conference, Seoul, Republic of Korea, 13–15 September 2004; pp. 141–161.
60. 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. [CrossRef]
61. 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. *Ann. Bot.* **2009**, *103*, 561–579. [CrossRef] [PubMed]
62. Yoshino, M. Climatic Change and Rice Yield and Production in Japan during the Last 100 Years. *Geogr. Rev. Jpn.* **1993**, *66*, 70–88. [CrossRef]
63. Shelley, J.I.; Nosaka, M.T.; Nakata, M.K.; Haque, M.S.; Inukai, Y. Rice Cultivation in Bangladesh: Present Scenario, Problems, and Prospects. *J. Int. Coop. Agric. Dev.* **2016**, *14*, 20–29.
64. 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. [CrossRef]
65. Nayar, N.M. Origin of African Rice, Book Chapter, 5. In *Origin and Phylogeny of Rices*; Academic Press: Cambridge, MA, USA, 2014; pp. 117–168.
66. Cultivation Practices: Water Management, Tamil Nadu University, India. Available online: http://www.agritech.tnau.ac.in/expert_system/paddy/cultivationpractices3.html (accessed on 29 March 2023).
67. Odhiambo, L.O.; Murty, V.V.N. Water Management in Paddy Fields in Relation to Paddy Field Layout. In *Proceedings of the International Workshop on Soil and Water Engineering, for Paddy Field Management*; Asian Institute of Technology: Bangkok, Thailand, 1992; pp. 377–384.
68. 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. [CrossRef]
69. Berkhout, E.; Glover, D.; Kuyvenhoven, A. On-farm impact of the System of Rice Intensification (SRI): Evidence and knowledge gaps. *Agric. Syst.* **2015**, *132*, 157–166. [CrossRef]
70. UphoV, N.; Fernandez, E.; Long-Pin, Y.; Jiming, P.; Sebastien, R.; Rabenanadrasana, J. Assessments of the system of rice intensification (SRI). In Proceedings of the International Conference, Sanya, China, 19–21 October 2002.
71. Lemi, T.; Hailu, F. Effects of Climate Change Variability on Agricultural Productivity. *Intl. J. Environ. Sci. Nat. Res.* **2019**, *17*, 14–20. [CrossRef]
72. 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. [CrossRef]
73. 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. *Clim. Chang.* **2002**, *52*, 331–343. [CrossRef]
74. 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. [CrossRef]
75. Chen, C.C.; McCarl, B.; Chang, C.C. Climate change, sea level rise and rice: Global market implications. *Clim. Chang.* **2011**, *110*, 543–560. [CrossRef]
76. 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.; et al. Review of Meteorological Drought in Africa: Historical Trends, Impacts, Mitigation Measures, and Prospects. *Pure Appl. Geophys.* **2022**, *179*, 1365–1386. [CrossRef]

77. 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*, 2973–2989. [CrossRef]
78. Rahman, A.N.M.R.; Zhang, J. Trends in rice research: 2030 and beyond. *Food Energy Sec.* **2022**, *12*, e390. [CrossRef]
79. GRiSP (Global Rice Science Partnership). *Rice Almanac*, 4th ed.; International Rice Research Institute: Los Banos, Phillippines, 2013; 283p.
80. 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. [CrossRef]
81. Terdoo, F.; Feola, G. The Vulnerability of Rice Value Chains in Sub-Saharan Africa: A Review. *Climate* **2016**, *4*, 47. [CrossRef]
82. 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. [CrossRef]
83. 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. Geogr.* **2019**, *102*, 71–83. [CrossRef]
84. 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*; International Rice Research Institute (IRRI): Los Banos, Philippines, 2010; pp. 411–431.
85. Pandey, S.; Paris, T.; Bhandari, H. Household income dynamics and changes in gender roles in rice farming. In *Book Chap: Rice in the Global Economy: Strategic Research and Policy Issues for Food Security*; International Rice Research Institute (IRRI): Los Banos, Philippines, 2010; pp. 93–111.
86. Rowhani, P.; Lobell, D.B.; Linderman, M.; Ramankutty, N. Climate variability and crop production in Tanzania. *Agric. For. Meteorol.* **2011**, *151*, 449–460. [CrossRef]
87. 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 Manag.* **2014**, *146*, 149–162. [CrossRef]
88. 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. [CrossRef]
89. Nwalieji, H.U.; Uzuegbunam, C.O. Effect of climate change on rice production in Anambra State, Nigeria. *J. Agric. Ext.* **2012**, *16*, 81–91. [CrossRef]
90. 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. [CrossRef]
91. 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. Royal Soc. Lond. B Biol. Sci.* **2014**, *369*, 20130089. [CrossRef] [PubMed]
92. 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. [CrossRef]
93. 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. [CrossRef]
94. 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*, 285–295. [CrossRef]
95. Morita, S.; Wada, H.; Matsue, Y. Countermeasures for heat damage in rice grain quality under climate change. *Plant Prod. Sci.* **2016**, *19*, 1–11. [CrossRef]
96. 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. [CrossRef]
97. World Rice Production, Consumption and Stocks, USDA. Available online: https://apps.fas.usda.gov/psdonline/reporthandler.ashx?reportId=681&templateId=7&format=html&fileName=World%20Rice%20Production,%20Consumption,%20and%20Stocks (accessed on 29 March 2023).
98. 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 Stud.* **2022**, *32*, 116–121.
99. Bouman, B.A.M.; Humphreys, E.; Tuong, T.P.; Barker, R. Rice and Water. *Adv. Agron.* **2007**, *92*, 187–237.
100. 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. *Agric. Sci.* **2013**, *4*, 35698. [CrossRef]
101. Lampayan, M.R.; Yadav, S.; Humphreys, E. Saving Water with Alternate Wetting Drying (AWD). International Rice Research Institute (IRRI). 2005. Available online: http://www.knowledgebank.irri.org/training/fact-sheets/water-management/saving-water-alternate-wetting-drying-awd (accessed on 3 February 2023).
102. Balasubramanian, V.; Hill, J.E. Direct seeding of rice in Asia: Emerging issues and strategic research needs for the 21st century. In *Direct Seeding: Research Strategies and Opportunities*; IRRI: Los Banos, Philippines, 2002; pp. 21–45.
103. 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 Manag.* **2002**, *57*, 11–31. [CrossRef]
104. 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. [CrossRef]

105. 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 Afr. Area Stud.* **2016**, *15*, 234–256.
106. IWMI. Alternate Wetting and Dry in Rice Cultivation. *Climate Adaptation through Innovation*. 2014. Available online: https://www.google.com.hk/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.nibio.no/en/projects/climaadapt/technical-briefs/_/attachment/inline/89cf553b-6cd4-4235-871d-1fa499f41129:a1f11777f5dfe8add4e297b5197576918002f05b/IWMI%2520Book%2520Final_AWD.PDF&ved=2ahUKEwjehcPO5IyHAxURh1YBHc_4CFsQFnoECBcQAQ&usg=AOvVaw2JIhRYmZIpy98s3XPaVNBK (accessed on 21 February 2023).
107. 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. [CrossRef]
108. 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. [CrossRef]
109. 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. Master's Thesis, The University of Tokyo, Tokyo, Japan, 2010.
110. 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. *Irrig. Drain.* **2019**, *68*, 679–689.
111. 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. [CrossRef]
112. 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 Proceedings of the 60th International Executive Council Meeting of the International Commission on Irrigation and Drainage (ICID), 5th Regional Conference, New Delhi, India, 9–11 December 2009.
113. Abrol, I.P.; Bhumbla, E.R.; Meelu, O.P. Influence of salinity and alkalinity on properties and management of rice lands. In *Soil Physics and Rice*; International Rice Research Institute: Los Banos, Philippines, 1985; p. 430.
114. 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 Manag.* **2004**, *70*, 67–81. [CrossRef]
115. 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. [CrossRef]
116. Xu, Z.; Zhou, G.; Shimizu, H. Plant responses to drought and rewatering. *Plant Signal. Behav.* **2010**, *5*, 649–654. [CrossRef]
117. 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.; et al. 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 Environ.* **2004**, *2*, 195–206. [CrossRef]
118. 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. [CrossRef]
119. Mahajan, G.; Chauhan, B.S.; Timsina, J.; Singh, P.P.; Sing, K. Crop performance and water and nitrogen use efficiencies in dry seeded rice in response to irrigation and fertilizer amounts in northwest India. *Field Crops Res.* **2012**, *134*, 59–70. [CrossRef]
120. 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. [CrossRef]
121. 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. [CrossRef]
122. 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; International Rice Research Institute: Los Banos, Philippines, 2013; 18p.
123. 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 Environ.* **2010**, *8*, 81–90. [CrossRef]
124. Rahman, R.; Sheikh, H.B. Effect of alternate wetting and drying (AWD) irrigation for Boro rice cultivation in Bangladesh. *Agric. For. Fish.* **2014**, *3*, 86–92. [CrossRef]
125. Ganesh, H.V. Effect of various irrigation schedules on yield and water use in transplanted paddy. Mysore. *J. Agric. Sci.* **2000**, *34*, 222–226.
126. 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. [CrossRef]
127. Yang, J.C.; Zhang, J.H. Crop management techniques to enhance harvest index in rice. *J. Exp. Bot.* **2010**, *61*, 3177–3189. [CrossRef] [PubMed]
128. 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. Protect.* **2014**, *6*, 895–901. [CrossRef]
129. 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. [CrossRef]

130. Ashouri, M. Water use efficiency, irrigation management and nitrogen utilization in rice production in the north of Iran. *APCBEE Proc.* **2014**, *8*, 70–74. [CrossRef]
131. Sariam, O.; Anua, A.R. Effects of irrigation regime on irrigated rice. *J. Trop. Agric. Food Sci.* **2010**, *38*, 1–9.
132. Buresh, R.J. Nutrient best management practices for rice, maize, and wheat in Asia. In Proceedings of the World Congress of Soil Science, Brisbane, Australia, 1–6 August 2010.
133. 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. [CrossRef]
134. Hamoud, Y.A.; Guo, X.; 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.
135. USDA. *Soil Taxonomy Report: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*; USDA-NRCS: Washington, DC, USA, 1999. Available online: https://www.nrcs.usda.gov/sites/default/files/2022-06/Soil%20Taxonomy.pdf (accessed on 27 February 2023).
136. Haque, A.N.A.; Uddin, K.M.; 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. *Agriculture* **2021**, *11*, 367. [CrossRef]
137. 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. [CrossRef]
138. Sander, T.; Gerke, H.H. Preferential flow patterns in paddy fields using a dye tracer. *Vadose Zone J.* **2007**, *6*, 105–115. [CrossRef]
139. Yoshida, S.; Adachi, K. Numerical analysis of crack generation in saturated deformable soil under-row-planted vegetation. *Geoderma* **2004**, *120*, 63–74. [CrossRef]
140. 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. [CrossRef]
141. 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. [CrossRef]
142. Liu, C.W.; Cheng, S.W.; Yu, W.S.; Chen, S.K. Water infiltration rate in cracked paddy soil. *Geoderma* **2003**, *117*, 169–181. [CrossRef]
143. 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. [CrossRef]
144. 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. Hydrol.* **2011**, *398*, 191–201. [CrossRef]
145. Sidle, R.C.; Kardos, T.L.; van Genuchten, M.Th. Heavy metals transport model in a sludge-treated soil. *J. Environ. Qual.* **1977**, *6*, 438–443. [CrossRef]
146. 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.; et al. Alternate wetting and drying irrigation for rice in Bangladesh: Is it sustainable and has plant breeding something to offer? *Food Energy Secur.* **2013**, *2*, 120–129. [CrossRef]
147. 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. [CrossRef]
148. Xu, X.Y.; McGrath, S.P.; Meharg, A.A.; Zhao, F.J. Growing rice aerobically markedly decreases arsenic accumulation. *Environ. Sci. Technol.* **2008**, *42*, 5574–5579. [CrossRef] [PubMed]
149. 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.J.; McGrath, S.P.; et al. Variation in grain arsenic assessed in a diverse panel of rice (*Oryza sativa*) grown in multiple sites. *New Phytol.* **2012**, *193*, 650–664. [CrossRef] [PubMed]
150. Brammer, H.; Ravenscroft, P. Arsenic in groundwater: A threat to sustainable agriculture in South and South-East Asia. *Environ. Int.* **2009**, *35*, 47–654. [CrossRef]
151. 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. [CrossRef]
152. 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. [CrossRef]
153. 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. Fertil. Soils* **2014**, *50*, 755–764. [CrossRef]
154. 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. [CrossRef]
155. 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. [CrossRef]
156. Kirk, G.J.D. *The Biogeochemistry of Submerged Soils*; Wiley: Chichester, UK, 2004; 304p.
157. 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. [CrossRef] [PubMed]
158. Meharg, A.A.; Norton, G.; Deacon, C.; Williams, P.; Adomako, E.E.; Price, A.; Zhu, Y.; Li, G.; Zhao, F.J.; McGrath, S.; et al. Variation in rice cadmium related to human exposure. *Environ. Sci. Technol.* **2013**, *47*, 5613–5618. [CrossRef] [PubMed]
159. Teramoto, S.; Uga, Y. Improving the efficiency of plant root system phenotyping through digitization and automation. *J. Arid Land Stud.* **2022**, *72*, 48–55. [CrossRef]

160. Teramoto, S.; Tanabata, T.; Uga, Y. RSAtrace3D: Robust vectorization software for measuring monocot root system architecture. *BMC Plant Biol.* **2021**, *21*, 398. [CrossRef] [PubMed]
161. Teramoto, S.; Takayasu, S.; Kitomi, Y.; Arai-Sanoh, Y.; Tanabata, T.; Uga, Y. High-throughput three-dimensional visualization of root system architecture of rice using X-ray computed tomography. *Plant Methods* **2020**, *16*, 66. [CrossRef]
162. 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. [CrossRef]
163. IPCC. Summary for Policymakers. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2011. Available online: https://archive.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf (accessed on 27 February 2023).
164. 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.
165. 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. In Proceedings of the American Geophysical Union, Fall Meeting 2018, Washington, DC, USA, 10–14 December 2018.
166. Lal, R. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degrad. Dev.* **2005**, *17*, 197–209. [CrossRef]
167. 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*, 65th ed.; Ladha, J.K., Duxbury, J.M., Hill, J.E., Gupta, R.K., Buresh, R.J.., Eds.; American Society of Agronomy: Madison, WI, USA, 2003; pp. 27–43.
168. 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. [CrossRef]
169. 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*, 43. [CrossRef]
170. 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. *PLoS ONE* **2015**, *10*, e0145268. [CrossRef] [PubMed]
171. 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 Manag.* **2021**, *247*, s106758. [CrossRef]
172. Jackson, R.D.; Idso, S.B.; Reginato, R.J.; Pinter, P.J. Canopy temperature as a crop water stress indicator. *Water Resour. Res.* **1981**, *17*, 1133–1138. [CrossRef]
173. 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. [CrossRef]
174. 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. [CrossRef]
175. 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 Manag.* **2022**, *266*, 107575. [CrossRef]
176. Siad, M.S.; Iacobellis, V.; Zdruli, P.; Gioia, A.; Stavi, I.; Hoogenboom, G. A review of coupled hydrologic and crop growth models. *Agric. Water Manag.* **2019**, *224*, 105746. [CrossRef]
177. 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.