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Impacts of Alternate Wetting and Drying Technology on Water Use and Soil Nitrogen Transformations for Sustainable Rice Production: A Review

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ABSTRACT

Rice is an important cereal crop cultivated in various soil types in Egypt. Furthermore, it is grown for multiple purposes, including export, consumption, and reclamation. In the agricultural sector, irrigated rice production is thought to use the most water, and growing water scarcity endangers this practice and this is a main sustainability challenge. One of the most popular irrigation techniques for saving water in flooded fields is alternate wetting and drying (AWD) which is considered a water management technique, practiced to cultivate irrigated rice with much less water than the traditional system. AWD irrigation system is a reliable and widespread water saving technology for rice production, moreover, it is a low-cost innovation that enables farmers to adapt to increasing water scarcity conditions, increase overall farm production efficiency, and mitigate greenhouse gas (GHG) emissions. Nitrogen (N) plays a vital role in maintaining rice production. Increasing N fertilizer applications has been a major measurement contributing significantly to crop yield improvement. The flooded conditions cause N to lose through surface runoff, leaching, and denitrification. AWD technology could also enhance rice growth, N absorption and accumulation, soil N transformation, nitrate content, ammonia-oxidizing bacteria abundance, and nitrate reductase activity. This review aims to evaluate AWD technology in water saving and sustaining rice production, nitrogen use efficiency (NUE), and GHG emissions particularly under climate change conditions and the challenges of water shortage. In addition to explaining the relationship of this technology to the soil N cycle to enhance the utilization of soil N under flooding conditions.

Keywords: Alternate wetting and drying, Water use efficiency, Nitrogen transformations, Nitrogen use efficiency, Rice sustainability.

INTRODUCTION

Rice (*Oryza sativa* L.) is the main source of staple carbohydrates for over half of the world's population (Abbas et al., 2019). For feeding, the expanding global population by 2035, an extra 116 million tons of rice will be required (Seck et al., 2012). To cultivate rice, water is needed in large quantities; one ton of rice grain takes about 2500 tons of water (Bouman, 2009). In this case, a major crisis to sustainable production is the combined increase in irrigation demand and the paucity of water (Surendran et al., 2021). Egypt is the Middle East's top producer of rice, producing 1.25% of world production annually (Eliw et al., 2022) and ranking first globally in terms of productivity (RRTC, 2013). Despite its success, Egypt still confronts difficulties in satisfying food demand and guaranteeing food security. According to statistics, only about 40% of the country's grain demand is provided by production (Ramadan, 2015). To meet food demands by 2050, agricultural production must increase by 70% (Elsadek et al., 2023).

Over the past 20 years, numerous technologies of water saving irrigation have been developed to increase water production and use less irrigation water. Chen et al., (2023) reported that water saving irrigation techniques play a crucial role in addressing water scarcity challenges and promoting sustainable agriculture. However, the selection of appropriate water saving irrigation methods remains a challenge in agricultural production. Additionally, the molecular regulatory mechanisms of crops under water saving irrigation are not yet clear. Furthermore, the integration of various technologies can stimulate new management strategies, optimize water resource utilization, and enhance sustainability, representing a major focus for future research. Water saving irrigation technologies is importance, when combined with genetic engineering, in addressing water resource scarcity, increasing crop yields, and promoting sustainable agriculture.

In flooded fields, alternate wetting and drying (AWD) has emerged as one of the most popular irrigation techniques for water saving (Song et al., 2020). This technique can save water requirement by up to 20–50% and improve water use efficiency (WUE) besides reducing greenhouse gas (GHG) emissions by 30–50% that have an impact on climate change. However, AWD has not been widely adopted, in part, due to the apprehension of yield reductions and hence demands greater efforts from researchers and extension workers. Safe AWD threshold level found to be 5–15 cm waterfall below the surface in field water tube that needs to be validated in different soil types and different climatic conditions. Proper management of water at a safe threshold is the foundation of AWD to realize potential yield while saving water (Faiz-ul Islam et al., 2020). The AWD technique has been actively promoted, especially in rice producing countries for example Egypt. This irrigation technology could decrease evaporation and deep percolation losses which can minimize water

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consumption. Also, it is associated with the direct seeding rice can reduce the water quantity applied while increasing or maintaining current yields (Materu et al., 2018).

Furthermore, AWD influences N movement and transformation, which has an additional effect on rice plant's nitrogen use efficiency (NUE) (Xu et al., 2019). The over application of nitrogen (N) fertilizers could cause nutrient losses (Chen et al., 2021), critical soil degradation (Guo et al., 2010) and GHG emissions (Chunmei et al., 2020). Therefore, studying how AWD technology affects NUE is becoming more important to minimize adverse environmental effects and maximize fertilizer N rates. Under low oxygen (O_2) conditions, the decay of soil N is slow and incomplete (Schlesinger, 1991), and it frequently results in the accumulation of organic compounds. The rhizosphere O_2 conditions are significant in paddy field ecosystems because of decreased soil N mineralization and nitrification, increased denitrification, and decreased soil N availability (Reddy and Gretz, 1998; Tian et al., 2018). Consequently, controlling the levels of O_2 in paddy soils to enhance rice's ability to utilize N is a practical solution to this issue.

This review aims to study AWD technology as one of the modern techniques for water saving and sustaining rice production, particularly under climate change conditions and the challenges of water shortage. It also aims to clarify the role of the cultivation method of rice in rationalizing water consumption. Moreover, to focus attention on the relationship of this technology to the soil N cycle to enhance the utilization of soil N under flooding conditions.

1. Rice crop and water crisis

The world's most important cereal crop is rice, it provides the majority of people with food and calories (Khush, 2005). Rice is the most common cereal crop cultivated on various soil types of Egypt. Furthermore, it is grown for multiple uses, including export, consumption, and as a reclaimed crop. Because of its submergence condition, rice despite being a salt sensitive crop is regarded as a reclamation crop for saline sodic soils (Zayed et al., 2017). The rice plant is semi-aquatic and has evolved to withstand submersion. Plants face several difficulties when completely submerged and internal aeration is one of the most important ones. In general, rice soils can withstand occasional flooding or waterlogging (Winkel et al., 2013). Nishiuchi et al., (2012) reported that rice, unlike other cereals, can grow well in paddy fields and is highly tolerant of excess water stress, from either submergence (in which part or all of the plant is under water) or waterlogging (in which excess water in soil limits gas diffusion). Rice handles submergence stress through internal aeration and growth controls. On the other hand, rice handles waterlogging stress by forming lysigenous aerenchyma (LA) and a barrier to radial O_2 loss (ROL) in roots in order to supply O_2 to the root tip as shown in Fig. (1).

This is why slow gas diffusion in water causes low O_2 levels in rice plants. However, rice roots are the main plant parts that adapt to changes in soil conditions, and they play a crucial part in how the plant reacts to water stress (Ghosh and Xu, 2014). There is ample evidence that changing the root structure of cereal crops cultivated in flood prone and nutrient deficient environments can boost their production by improving their ability to absorb soil nutrients (Lynch et al., 2014). The agriculture industry's is the biggest water user (Thakur et al., 2014) wherein 79 million hectares of irrigated paddy fields provide more than 75% of the world's annual rice supply where the fields are typically continuously flooded through the season of plant growth (IRRI, 2017). Therefore, irrigated rice production is considered the greatest water consumer in the agriculture sector, and its sustainability is threatened by water scarcity, particularly in Egypt after the establishment of the Al Nahda dam in Ethiopia (Thakur et al., 2011), due to increasing urbanization, industry, leisure, and agriculture growth. For these reasons, fresh water availability for irrigation decreases. This is a major sustainability challenge as water shortage threatens the irrigated rice systems production (Bergez and Nolleau 2003; Abd El-Mageed et al., 2021).

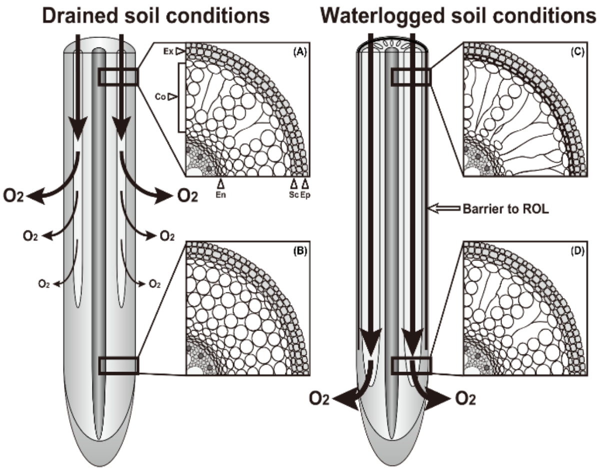

Fig. 1. Rice plant mechanism for tolerant the drained or waterlogging conditions: under drained soil conditions, LA is constitutively formed at the basal part of the roots (A), but it is not usually formed at the apical part of the roots (B). Under waterlogged soil conditions, LA is induced at the basal part (C) and the apical part (D) of the roots. LA is more highly developed at the basal part of the roots (A, C) than at the apical part (B, D). Arrow thickness reflects the amount of O_2 available. Ep: epidermis, Ex: exodermis, Sc: sclerenchyma, Co: cortex, En: endodermis. Adapted from Nishiuchi et al., (2012)

Fresh water is becoming increasingly a challenge for nearly four billion people, due to population expansion, expanding industrial and urban development, and decreased availability in response to pollution and resource depletion, as well as irrigation. Furthermore, the rice demand is expected to expand in the future as a result of climate change and the increasing population (Bouman et al., 2007), especially in arid and semi-arid regions (Hozayn et al., 2016). Water is needed in huge amounts for the cultivation of rice; one ton grain of rice takes about 2500 tons of irrigation water (Bouman, 2009). According to estimates, by 2025, approximately15–20 million hectares of rice fields in Asia (more than 10% of all paddy fields worldwide) will suffer some extent of water shortage (Tuong and Bouman, 2003). Therefore, research on innovative irrigation techniques to lower irrigation water and increase water productivity needs to be done without causing any harm to the environment. Generally, the sustainability of traditional irrigated rice cultivation is being threatened by rainfall variability brought on by climate change, declining groundwater levels, and ineffective use of water (Mote et al., 2023).

Egypt is the driest nation in the Nile Basin and depends almost completely on the River Nile's irrigation water with 55.5 billion m^3 $year^{-1}$. Its reliance ratio on all renewable water resources is 97%, according to (Ashour et al., 2009), roughly 90% of the water available is used for agriculture. As a result, it is critical to find novel ways to conserve more irrigation water (El-Metwally et al., 2015). Rice production consumes about 11 billion m^3 of irrigation water with 20% of all amount of irrigation water used in agriculture under the Nile Delta of Egypt. Therefore, it is appropriate for the government to intend to cut back on current rice plantings by almost 50%, or more than two million feddan. Furthermore, new cultivars with quick maturation periods are released by the Egyptian National Program of Rice Research to cut local water consumption by 20–30%. Also, Hunter et al., (2017) confirmed that the water situation in Egypt is critical and reached the population predictions for 2025 that per capita water share might go down to less than 500 m^3 with indicators of a sharp decline in surface and groundwater quality. The total amounts of milled rice consumed, produced, and exported by Egypt were 3.28, 3.74, and 1.07 million tons, respectively (Hunter et al., 2017). However, rice production has grown exponentially in recent years, surpassing the previous three estimated. On the agricultural map, rice has mostly taken the place of cotton and maize fields as the most significant summer crop. Furthermore, in certain regions of the North Delta, rice farming is crucial for maintaining soil fertility and lowering the risk of salinity. Increasing crop water productivity can help the agriculture sector meet its main challenge of producing more food with less water (Okasha et al., 2013; Zwart and Bastiaanssen, 2004) particularly in Egypt (Abdelraouf et al., 2013).

2. Cultivation methods of rice in Egypt

There are various methods used around the world to cultivate rice. The most significant methods of cultivation are: (i) the direct seeding rice (DSR) or broadcasting seed technique which directly broadcasting seeds (wet or dry) onto the topsoil of flooded fields, (ii) traditional transplanting rice (TPR) seedlings from a nursery (Chen et al., 2009), and (iii) drilling seeding rice (DRSR). According to Akhgari and Kaviani, (2011) DSR can be done in three main ways: (i) dry seeding, which involves sowing dry seeds into dry soil; (ii) wet seeding, which involves sowing pre-germinated seeds into dry soil; and (iii) water seeding, which involves sowing seeds into standing water. Furthermore, the absence of seedbeds makes the broadcasting method a quick and easy crop establishment strategy in rice fields, with a short turnaround time between crops. According to earlier studies, plants sown in irrigated paddy fields produced higher grain than plants transplanted into the same area (San-oh et al., 2004). The agricultural practices followed in DSR cultivation systems are shown in Fig. (2).

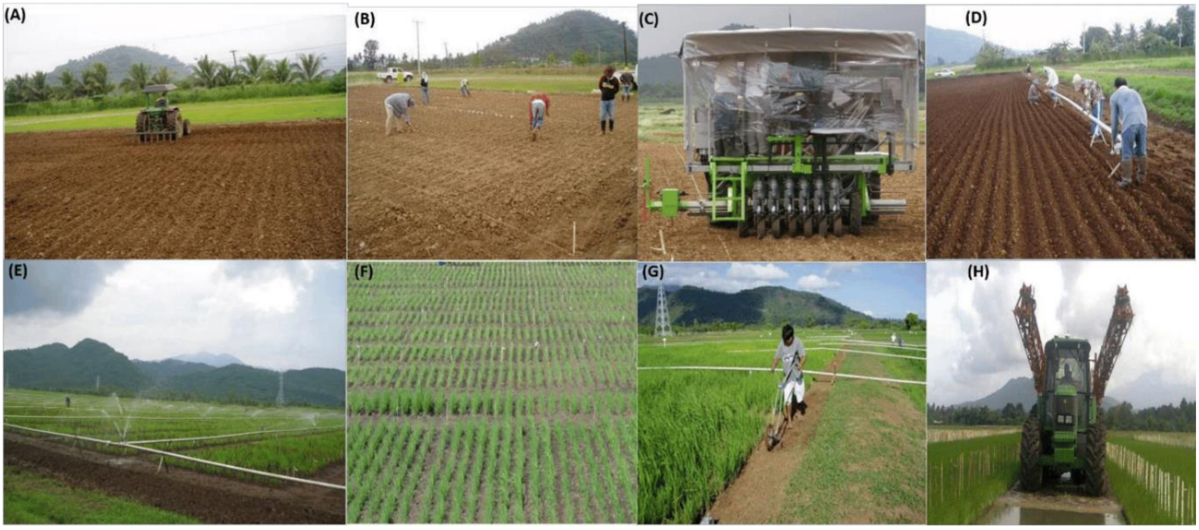

Fig. 2. The agricultural practices followed in DSR cultivation systems: (A) land preparation, (B) manual seed sowing, (C) seed showing using mechanized seed drill, (D) installation of sprinkler irrigation system, (E) irrigation through sprinkler system at seedling stage, (F) field view of DSR field at seedling stage, (G) manual weed control using wheel hoe, and (H) mechanized weed control using boom tractor sprayer. Adapted from Sandhu et al., (2021)

Additionally, Liu et al., (2015) compared dry DSR and transplanted flooded rice, and reported that dry DSR is an alternative cropping technique that should require less water and labor than classical transplanted flooded rice. For dry DSR, they grew three rice cultivars and maintained aerobic conditions up to the five leaf stage followed by anaerobic conditions until maturity. The grain yield of DSR, of 9.01 Mg ha^{-1}, is identical to the grain yield of transplanted flooded rice, across cultivars and for both years. Moreover, dry DSR uses 15.3% less water than transplanted flooded rice and increased the grain NUE by 20.3% in 2012 and 11.2% in 2013 Fig. (3).

The DRSR depends on dropping seeds in lines and spots. Spots of certain measurements created seeds secured with soil and compacted. The soil surface could also be rutted or leveled once seeded. During seeding operations, it may be added fertilizers, pesticides at the same time. Seeds are cultivated in bunches of two to three at a homogenous between them (Venkata Reddy et al., 2021). The DRSR technique maintains a uniform plant populace per unit range per running meter within the rows, thus the rate of seeding decreases. It enhances the diminishing of unhealthy and powerless plants. Simple wheel tools provide for efficient weeding in a short amount of time. The DSR method could be done using a sowing gadget that sows the rice seeds by situating them into the soil at the proper depth. Rice seeds are covered with soil to a suitable depth, ensuring that the seeds are covered with soil to save it from being eaten by birds (Cheng, 2021).

Fig. 3. Soil preparation: (A) for dry DSR, and (B) for traditional transplanted flooded rice. Water management in dry DSR: (C) before irrigation, and (D) after irrigation. Adapted from Liu et al., (2015)

In several Asian countries over the past two decades, a shift in plant cultivation methods from manual transplanting to direct seeding has occurred in response to rising production costs, particularly those of water and labor (Rao et al., 2007). The advantages of DSR over TPR include good standing, higher tillering, stable growth, better pest control, low fertilizer requirements, sometimes higher grain yield, better water management, less risk due to drought and flooding damage and offers the opportunity to save both time and labor (Farooq et al., 2007). According to Qureshi et al., (2006) the transplanting method required 1130 mm per season of irrigation water, whereas dry DSR needed an average of 865 mm. This suggests using the direct dry sowing method could save 23% of the water. About 43 and 56% of the total water input was lost through percolation losses for direct dry rice and old seedling rice, respectively. Regarding conserving water, dry direct seeding outperforms transplanting in terms of efficiency and effectiveness.

On the other hand, in direct seeding, there are some problems such as weeds spreading, high seeding rate, and the necessity for land leveling. At present, with the high demand for improved production at low requirements, there is an urgent need to identify suitable rice genotypes under the broadcasting method with low seeding rates and to modify crop management to approach yield perfectly. For soil water managements, in transplanting, wet DSR, and dry DSR methods, the total water requirements for growing rice crop were 1041, 942, and 915 m^3 ha^{-1}, respectively. The WUE was lowest under dry DSR and highest under wet DSR. The wet DSR and wet DRSR showed 9.7 and 24.0% higher WUE, respectively than the conventional TPR method. Compared to TPR, wet DSR required 5–20% less labor. Additional laborers were needed in DRSR for the sowing process, but these methods were found that render weeding easier and use less labor. The findings show that wet DRSR planting is a better technique than current ones, yielding a higher yield with less water requirements and labor and simple weed control (Thakur et al., 2004). However, Badr et al., (2007) stated that the maximum seed productivity was obtained by the TPR method as compared to the DRSR method. Furthermore, Sandhu et al., (2021) proved that paddy production through a conventional puddled system of rice cultivation is becoming more and more unsustainable economically and environmentally as this method is highly resource intensive and these resources are increasingly becoming scarce. The ongoing large scale shift from a puddled system of rice cultivation to DSR necessitates a convergence of breeding, agronomic and other approaches for its sustenance and harnessing natural resources and environmental benefits. Current DSR technology is largely based on agronomic interventions applied to the selected varieties of TPR. In DSR, poor crop establishment due to low germination, lack of DSR adapted varieties, high weed nematode incidences and micronutrient deficiency are primary constraints.

3. Alternate wetting and drying and its potential on rice yield

Over the past twenty years, several water saving irrigation technologies, including aerobic rice systems (Jabran and Chauhan, 2015), dry DSR (Alam et al., 2020), and AWD irrigation (Lampayan et al., 2015), have been developed to decrease irrigation water and increase water productivity. Among these, AWD has emerged as one of the most popular irrigation techniques for saving water in paddy fields (Song et al., 2020). It is a water management strategy that uses less water to cultivate rice than the traditional method of intermittent and controlling irrigation to maintain continuous standing water in the crop field. Prolonging irrigation intervals, the use of early rice varieties, and effective weed control are some of the requirements for a successful water saving strategy. During the growing season, irrigation every few days produces a respectable rice yield. Numerous studies have demonstrated that rice typically grows more quickly in shallow water than it does in deep water. When rice is continuously flooded, it grows and yields more than if it subjects to water deficits during specific growth stages (Song et al., 2020).

The AWD, which is gaining popularity as a means to reduce the need for irrigation water in rice fields without lowering output, is one method of water management programs. The typically continuously flooding system of rice production is a main source of rice production, however during the cropping season, it requires a significant amount of water input, up to 9000 m^3 fed^{-1} (Ishfaq et al., 2020). AWD applies irrigation water a few days following the ponded water's absence. As a result, the field experiences periodic flooding and non-flushing. Depending on several variables, including soil texture, weather, and crop growth stage, the interval between irrigations can range from one to over ten days of dry soil. While AWD encourages rice plants to consume less water, it may also directly impact the physical characteristics of the soil and the growth of roots (Zhang et al., 2009). Furthermore, Nour et al., (1994) found that exposure of rice plant to water stress considerably decreases the number of tillers per plant, plant height, and grain yield. Moreover, they reported that rice plants can withstand a water shortage for twelve days to four weeks after transplanting. They concluded that increasing irrigation intervals from four to twelve days resulted in the most irrigation water savings. For Egyptian rice fields, six day irrigation intervals are recommendable.

Three rice irrigation techniques in Tanzania using the system of rice intensification (SRI) as compared to the traditional continuously flooding system (CF). The suggested systems included: (i) CF (50 mm for the whole season), (ii) SRI (40 mm for three days followed by no irrigation for five days), (iii) 80% SRI, and (iv) 50% SRI. For the dry season, the SRI and 80% SRI produced higher yields of 9.68 and 11.45 tons ha^{-1} and saved 26 and 35% of water, respectively compared to the CF (8.69 tons ha^{-1}). The 50% SRI had the lowest yield by 7.48 tons ha^{-1}. The 80% SRI treatment outperformed all other treatments over with an additional yield of 1.57 tons ha^{-1} and 33% (345 mm) water savings compared to the CF. Water saved by converting from the CF to the 80% SRI (1.98 million ha) can support a 50% expansion in the current rice irrigated area in Tanzania. Even without irrigation expansion, the 80% SRI can increase rice production by 1.5 million tons annually (Materu et al., 2018). Yoshida and Hallett, (2008) found that mechanical resistance was greatly enhanced when rice soils were dried to a matric potential (Ψ_m) of –50 kPa, subsequent wetness did not influence this resistance. Bottinelli et al., (2016) state that macro-pores can sprout out of pre-existing cracks and create networked pore networks that promote quick root development. In contrast, a severe AWD (re-flooded when soil Ψ_m reached –30 kPa) limits rice root growth and lowers grain output.

A moderate AWD can promote rice root growth and improve grain yield (Carrijo et al., 2017; Zhang et al., 2009). Zhang et al., (2023) reported that AWD improved water consumption efficiency by 31% as compared to continuous flooding (CF) but at an average yield penalty of 6%. During the rice growing season, optimal AWD was used when water potential was kept at Ψ_m higher than (–15 kPa) and water depths lower than 18.5 cm. A conceptual diagram of AWD influencing rice yield is illustrated in (Fig. 4), changes in total organic carbon, pH and NO_3^- in soil act as the driving indicators underpinning the effect of AWD on yield. Integrated AWD strategies amplify the beneficial effects of soil properties and increase yield and WUE by 1~7% and 23~52%, respectively. This technology also could decrease evaporation and deep percolation losses which can minimize water consumption. Also, it associated with the DSR can reduce the quantity of water applied while maintaining or increasing current yields (Materu et al., 2018).

Frequency and long periods without flooded conditions (AWD systems) depends on some factors such as: (i) climate conditions, (ii) soil type (Zhang et al., 2009), (iii) soil hydrological conditions, the potential of soil increasing from 0 to –30 kPa and schedule of drying periods (Yang et al., 2007; Zhang et al., 2009), (iv) depth of groundwater table, (v) rice variety, and (vi) crop management viz., N fertilization (Tabbal et al., 2002). The duration, actual frequency and water stress degree during the non-flooded periods are probably the most critical factors affecting rice production (Belder et al., 2004). The process of AWD is conducted from the tillering to the grain filling stage. In this instance, seepage and percolation of unproductive irrigation water into drains, creeks, or groundwater can be reduced by AWD technology (Akpoti et al., 2021).

The AWD technology has an impact on soil properties such as organic carbon (OC) and the macronutrient content including soil pH and available N, P, and K substantially affects rice growth and grain yield (Atere et al., 2017; Kopittke et al., 2022). Increasing OC can provide a great quantity of substrate for microbial growth in soil (Kopittke et al., 2022), and change soil structure by forming macro-aggregates (Audette et al., 2021). These previous factors together, can increase plant available water as a result of increasing water holding capacity (Bo et al., 2022). Regarding Zhang et al., (2023) they showed that changes in pH, OC and $N\text{-}NO_3^-$ in soil had a significant influence on rice yield. Yield improvements of 5–7% were obtained when available K and OC in soil higher than 0.18 and 27.83 g kg^{-1}, respectively, under Ψ_m higher than (–40 kPa) (Fig. 6). The comparisons between AWD technology and the CF method on rice yield under different soils are illustrated in Table (1).

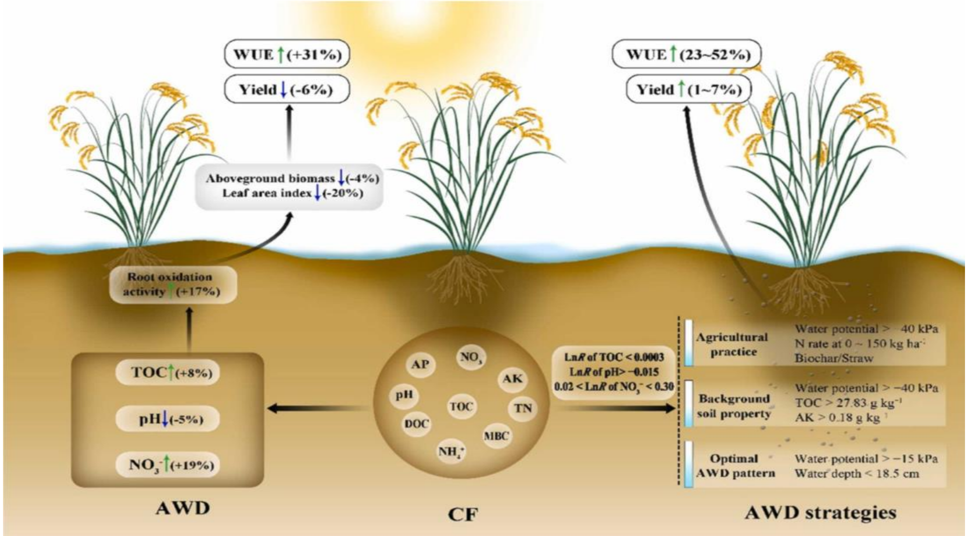

Fig. 4. Conceptual diagram of AWD influencing rice yield: (↑) denote positive responses, (↓) denote negative responses. AWD: alternate wetting and drying irrigation, CF: continuous flooding, WUE: water use efficiency, TOC: total organic carbon, DOC: dissolved organic carbon, MBC: microbial biomass carbon, TN: total nitrogen, AP: available phosphorus, AK: available potassium. Adapted from Zhang et al., (2023)

Table 1. Comparisons between AWD technology and CF method on rice yield

Soil properties			AWD		Water use	Country	Reference
Texture	pH	OC (%)	Stage	Degree			
Clay	7.8	NA	T	M/E	Yes	Iran	Abbasi and Sepaskhah (2011)
Clay	6.7	2.0	T	E	Yes	Philippines	Belder et al., (2005)
Clay	6.7	2.0	V/T	M/E	Yes	Philippines	Cabangon et al., (2011)
Non clay	7.1	0.6	T	NA	Yes	India	Geethalakshmi et al., (2011)
NA	7.8	0.5	T	NA	Yes	Pakistan	Jabran et al., (2015)
Clay	6.4	0.9	T	NA	NA	Bangladesh	Khan et al., (2015)
Non clay	7.4	0.5	T	M/E	NA	India	Khosa et al., (2011)
Non clay	7.4	3.0	T	NA	NA	China	Li (2012)
Non clay	6.7	4.2	T	NA	NA	India	Singh et al., (2009)
Clay	6.8	1.2	T	NA	Yes	China	Tan et al., (2013)
Non clay	NA	2.5	V/R	M/E	Yes	China	Yang et al., (2007)
Non clay	NA	2.5	R	E	Yes	China	Zhang et al., (2010)

pH: potential of hydrogen ions; OC: organic carbon; AWD stage (T: throughout the season, R: reproductive and V: vegetative); AWD Degree (M: moderate and E: extreme); Water use (Yes: available data and NA: not available data).

Because rice is growing under wide salt affected regions but with low yields, increasing rice productivity under these soils is significant in raising the average yield generally (Hagrus et al., 2011). Rice cultivation could wash salts in the soil and gradually minimize damage and improve the properties of the soil until the soil reforms by reducing the concentration of salts (Zaki, 2016). Applying farmyard manure (FYM) to soil that is irrigated with saline water may have a greater impact on maintaining soil resistance against degradation. As a result, applying FYM to irrigated soils with low water quality can help in rice production sustainability, especially if saturated conditions are not permanently available (Mansour et al., 2015; Mansour and Soliman, 2022). Also, the addition of FYM with the AWD technique could be effective in GHG mitigation strategies for reducing global warming potential (GWP) without sacrificing rice yield (Pramono et al., 2022).

However, although rice experts at different research institutions have supported conventional irrigated flooded rice production systems, it has not been able to achieve yield gains that would encourage farmers to lower their irrigation rates (Thakur et al., 2014). Riaz et al., (2018) reported that continuous AWD may result in poor soil health caused by carbon loss, nutrient depletion, cracking, and affecting soil physical properties (Fig. 5). Biochar has a great scope to overcome these problems by improving soil's physicochemical properties (Coumaravel et al., 2011). It efficiently retains nutrients and supplies as a slow release fertilizer, which may restrict preferential nutrient loss through soil cracks under AWD. It also improves soil's physical properties, slows cracking during drying cycles, and enhances water retention by storing moisture within its internal pores. Straw and or biochar addition under Ψ_m with low rate application of N enhanced the positive effects of soil C and N, resulting in a 2–3% increase in yields.

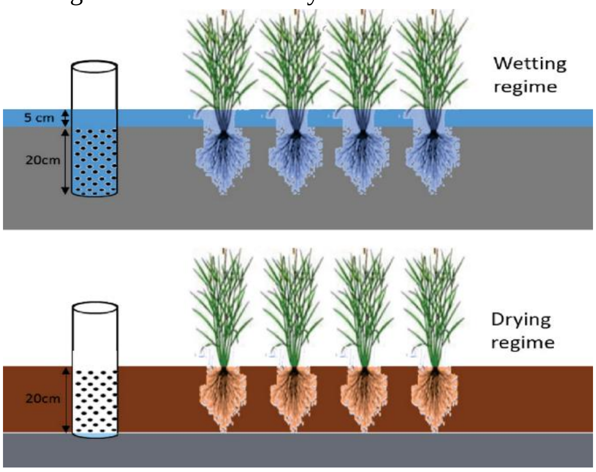

Fig. 5. Alternate wetting and drying irrigation technology for rice. Adapted from Riaz et al., (2018)

4. Nitrogen fertilization and its relationship to rice yield

For optimal rice production, fertilizer is a significant input for increasing rice production, wherein yields and output quantities affect the profitability of rice production systems (Khuang et al., 2008). The N fertilizer provides the greatest response. It is one of the most significant agronomic inputs and limiting factors in achieving the world's potential for rice grain output and quality (Noor 2017; Samonte et al., 2006; Wu et al., 2016). Nitrogen is considered one of the most crucial nutrition nutrients for rice growth in natural ecosystems (Fageria and Baligar, 2003). Using an adequate N rate is important not only for producing a maximum economic yield but also for minimizing environmental pollution. Alam et al., (2023) stated that a large amount of N fertilizer is required for paddy cultivation, but NUE in paddy farming is low (20–40%). Much of the unutilized N potentially degrades the quality of soil, water, and air and disintegrates the functions of different ecosystems. More efficient N management tools are yet to be developed through research and extension. Awareness raising campaign among farmers is necessary against their misunderstanding that higher N fertilizer provides higher yields. The sources and losses of N in wetland rice ecosystem are shown in Fig. (6). The NUE, as the ratio of N outputs in the harvested product to N inputs, including from fertilizer and natural processes, and has also been called N removal efficiency is illustrated in Fig. (7).

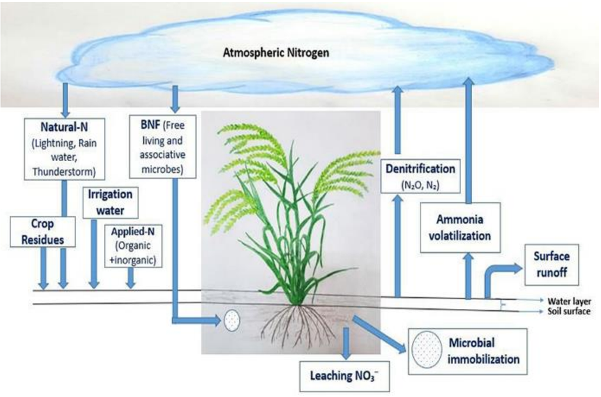

Fig. 6. Sources and losses of nitrogen in wetland rice ecosystem. Adapted from Alam et al., (2023)

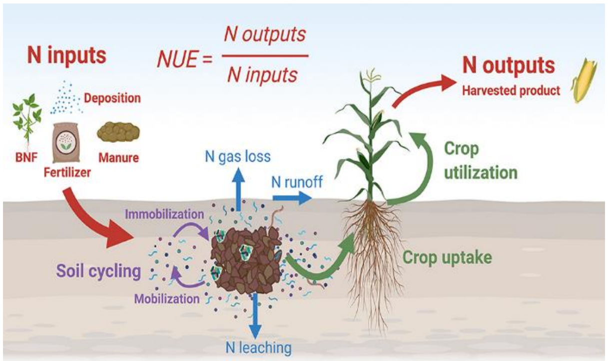

Fig. 7. Soil N cycle: N inputs to the system (red arrow - BNF is biological N fixation) will cycle through the soil (purple arrows), are susceptible to environmental losses (blue arrows), and are eventually used by crops (green arrows) with a portion harvested or removed (red arrow). Adapted from Udvardi et al., (2021)

Great amounts of post-harvest residual soil N can accumulate as a result of excess use of N fertilizer (Ladha et al., 2016). Although the residual N in the soil may be used for crops in the upcoming seasons, it is very prone to leaching during non-cultivation. In addition, agronomic features of different rice varieties can influence their response to N fertilizer. Through translocation, the absorption of N helps rice growth, especially in the vegetative stages such as reproduction and grain filling (Bufogle et al., 1997). Also, it is observed a significant increase in N (Tiwari et al., 2000) and P (Hussein and Radwan, 2001) of rice grain yield with different applied levels of N fertilizers. El-Sheref et al., (2004) found that grain yield and N content in rice crop increased significantly with increasing N dose. The required optimum N rate depends on several factors, including the yield potential of variety, soil textures, water management practices, soil contents of P and K and the intensity of insects, diseases and weeds. El-Batal et al., (2004) observed that there was a considerable improvement in plant height, panicle length, number of filled grains per panicle, and grain yields when N application was increased from 120 to 190 kg N ha^{-1}. Also, Ebaid and Ghanem, (2000) reported that rice plant growth, yield and yield components significantly improved when N dose increasing up to 144 kg N ha^{-1}.

According to the importance of N to rice plant, it influences rice yield by playing a critical role in photosynthesis, efficient tillering, spikelet formation, enhances seed yield and biomass accumulation subject to the efficient water supply. Furthermore, N contributes to the formation of carbohydrates in rice crop culms and leaf sheaths before heading as well as in the grain during ripening (Yoshida et al., 2006). In several cases, farmers utilize imbalanced doses of N fertilizers, resulting in a greater incidence of pests or insects attack, reducing rice yield. On the other hand, lack of N results in stopped growth, poor vegetative and reproductive performance, pale yellow color and small grain size (Awan et al., 2011). Moreover, Chamely et al., (2015); Rahman et al., (2007) recorded that great yielding recent rice varieties offer a higher response for N application, while they differ in N requirements depending on their agronomic features and genotype in several climatic conditions to exploit their complete yield potential.

5. Nitrogen fertilization and its relationship to aerobic irrigation

One significant agricultural technique that is essential to the production of rice is aerobic cultivation. The goal of this technique is reducing irrigation while increasing yields (Kato and Okami, 2010). The growth, root physiology, and N absorption of rice can be impacted by a variety of aeration techniques, including chemical aeration, which involves fertilizing rice plants with CaO_2 during the tillering and booting stages, and AWD which also known as aerobic irrigation (Zhao et al., 2009). The AWD affects the transformation and mobility of N, which further affects the NUE of rice plants. The NUE measures a plant's capacity to absorb, assimilate, translocate, and reuse N. A variety of factors influence this capacity, including the type of fertilizer used, varietal traits, soil and water management practices, and environmental factors (Xu et al., 2019).

According to FAO, (2017) there was a 20% increase in the demand for synthetic N fertilizer globally in 2020, surpassing 118 million tons. Farooq et al., (2022) reported that the abundance and structural composition of N transformation related microbial communities under certain environmental conditions provide sufficient information about the N cycle under different soil conditions. Two types of microorganisms, ammonia-oxidizing archaea and ammonia-oxidizing bacteria majorly conduct biological ammonia oxidation. The variations in soil properties significantly affect the structural composition and abundance of ammonia-oxidizers. Variations in soil properties are more influential in the community structure and abundance of ammonia-oxidizers than the application of synthetic N fertilizers and nitrification inhibitors. The internal soil N cycling is illustrated in Fig. (8).

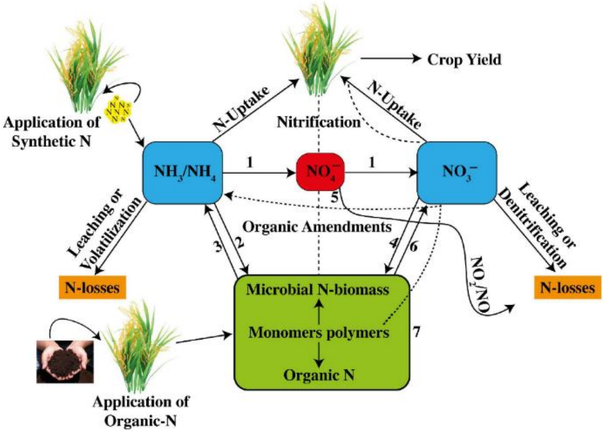

Fig. 8. Internal soil N cycle is comprised of: nitrification, ammonification, NH_4^+ immobilization, NO_3 immobilization, dissimilatory NO_3 reduction to NH_3, heterotrophic nitrification, and plant N uptake. Adapted from Norton and Ouyang, (2019)

The excessive use of N fertilizers could cause critical nutrient losses (Chen et al., 2021), soil degradation (Guo et al., 2010), and GHG emissions (Chunmei et al., 2020). Therefore, studying how AWD affects NUE is becoming more important to minimize adverse environmental effects and maximize the rates of N fertilizer. Because of its unique growth behavior of rice, it differs from other crop species in how it transforms and uses N in paddy fields. In low O_2 conditions, soil N decay is slow and incomplete (Schlesinger, 1991), and it frequently results in the accumulation of organic compounds. The rhizosphere O_2 conditions are significant in paddy field ecosystems because of decreased soil N mineralization and nitrification, increased denitrification, and decreased soil N availability (Reddy and Gretz, 1998; Tian et al., 2018). Consequently, controlling the O_2 levels in paddy soils to enhance rice's ability to use N is a practical solution to this issue.

For these reasons, the AWD technique enhanced rice growth, N absorption and accumulation, and soil N transformation, reflecting an increase in leaf area, N uptake and accumulation, nitrate reductase activity, soil NO_3^- content, nitrification activity, and abundance of ammonia-oxidizing bacteria. This may be due to increased soil O_2, which changed the soil N cycling. However, throughout the rice growth period, there was no discernible change in pH or soil microbial biomass carbon (Chunmei et al., 2020). In addition, O_2 conditions in the rhizosphere have an impact on microbial activity, pH level, ion morphology, and soil redox potential. Moreover, these variables influence N absorption and use in rice as well as N transformation in soil, either directly or indirectly (Li and Wang, 2013; Yan et al., 2019).

The soil N can readily change from one form to another, such as from NH_4^+ to NO_3^-, because it is mobile and dynamic (Cao et al., 2016). The distribution and shape of N in the soil are influenced by O_2 levels in the soil. Furthermore, rice reacts differently to different nutrients under varied soil O_2 levels. Although NH_4^+ is typically thought of as the ideal N source for rice, NO_3^- plays an important function in rice growth as well. The advantages of NO_3^- for rice are evident in certain situations (Duan et al., 2006). In both hydroponic systems and soils, the simultaneous application of NH_4^+ and NO_3^- enhances plant development, raises dry matter accumulation and yields, and enhances N absorption and use (Qian et al., 2004; Ruan et al., 2007; Wang et al., 2016).

On the other hand, the alternating periods of anaerobic and aerobic conditions in AWD typically increase N_2O emissions through the processes of anaerobic denitrification (Fertitta-Roberts et al., 2019) and aerobic nitrification (Tran et al., 2018). As a result, in paddy soils, AWD subsequently influences yield-scaled global warming potential (YGWP) and global warming potential (GWP). The AWD technology can lower GWP and YGWP, as numerous earlier research have shown (Faiz-ul Islam et al., 2020; Oo et al., 2018). According to CO_2 equivalency, CH_4 emissions typically contribute significantly more to GWP than N_2O emissions (Mofijul Islam et al., 2020). A few studies, nevertheless, have found no evidence of a substantial difference in GWP between continuous flooding and AWD (Singha et al., 2019). This is may be attributed to significantly higher N_2O emissions more than offset the decrease in CH_4 emissions (Ku et al., 2017).

CONCLUSION

Wet-dry cycles of AWD (alternate cycles of flooded and unflooded conditions) are likely to result in significant changes in soil hydrology consequently in the rice yield, nitrogen transformations, nitrogen use efficiency, water use efficiency, and greenhouse gas emissions which in turn achieving the sustainable cultivation of rice. Overall, AWD lowered yields by 5.4%; however, under moderate AWD. For example, when soil matric potential was less than –20 kPa or field water level did not fall below 15 cm from the soil surface, yields were not significantly decreased in most conditions. In contrast, extreme AWD (when soil matric potential increased more than –20 kPa) resulted in a yield reduction of 22.6% compared to continuous flooding rice systems. For water use efficiency, it was lowest under extreme AWD while, under moderate AWD water use was dropped by 23.4% compared to continuous flooding rice systems. The collected data highlight the possibility of using AWD to decrease water inputs without compromising the yield of rice crop. Finally, AWD technique is a promising management strategy, but more work has to be done to convert the findings to the field and irrigation district scales, where different constraints can arise.

Abbreviations

AWD: alternate wetting and drying, CF: traditional continuously flooding system, DRSR: drilling seeding rice, DSR: direct seeding rice, GHG: greenhouse gas, GWP: global warming potential, LA: lysigenous aerenchyma, N: nitrogen, NUE: nitrogen use efficiency, OC: organic carbon, ROL: radial O_2 loss, SRI: system of rice intensification, TPR: traditional transplanting rice, WUE: water use efficiency, and YGWP: yield-scaled global warming potential.

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تأثيرات تكنولوجيا الترطيب والتجفيف المتبادل على استخدام المياه وتحولات نيتروجين التربة من أجل الإنتاج المستدام للأرز

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الملخص

الأرز محصول حبوب مُهم يزرع بأنواع مختلفة من الأراضي في مصر. علاوة علي ذلك، يتم زراعته لأغراض مُتعددة، بما في ذلك التصدير والاستهلاك والاستصلاح. في القطاع الزراعي، يستهلك إنتاج الأرز المروي معظم المياه، وتهدد ندرة المياه المتزايدة هذه الممارسة مما يشكل تحديًا رئيسيًا للاستدامة. إحدى تقنيات الري الأكثر انتشارًا لتوفير المياه في الحقول المغمورة هي الترطيب والتجفيف المتبادل والتي تعتبر أسلوبًا لإدارة المياه، يُمارس لزراعة الأرز المروي بكمية مياه أقل بكثير من النظام التقليدي. تعد هذه الطريقة تقنية موثوقة، واسعة النطاق لتوفير المياه لإنتاج الأرز، علاوة علي ذلك، فهي ابتكار مُنخفض التكلفة يُمكّن المزارعين من التكيف مع ظروف ندرة المياه المتزايدة، وزيادة كفاءة الإنتاج الزراعي بشكل عام، والتخفيف من انبعاثات الغازات الدفيئة. يؤدي النيتروجين دورًا حيويًا في الحفاظ علي إنتاج الأرز، كانت زيادة استخدام الأسمدة النيتروجينية من المقاييس الرئيسية التي ساهمت بشكل كبير في تحسين إنتاجية المحاصيل. تتسبب ظروف الغمر في فقد النيتروجين من خلال الجريان السطحي، والغسيل، وعكس التأزت. يُمكن لهذه التكنولوجيا أيضًا أن تعزز نمو الأرز، وامتصاص وتراكم النيتروجين، وتحوله بالتربة، ومحتوي النترات، ووفرة البكتيريا المُؤكسدة للأمونيا، ونشاط اختزال النترات. تهدف الدراسة إلي تقييم تكنولوجيا الترطيب والتجفيف المتبادل في توفير المياه واستدامة إنتاج الأرز، وكفاءة استخدام النيتروجين، وانبعاثات الغازات الدفيئة خاصة في ظل ظروف تغير المناخ وتحديات نقص المياه. بالإضافة إلي شرح علاقة هذه التقنية بدورة النيتروجين في التربة لتعزيز الاستفادة من النيتروجين تحت ظروف الغمر.