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Soil Biogeochemical Responses and Yield Performance of Rice Under Contrasting Irrigation Regimes in A Kenyan Paddy Agroecosystem

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I. INTRODUCTION

1.1 Background Information

Rice (*Oryza sativa*) is a staple food for more than half of the world's population (Bin & Zhang, 2023). Therefore, there are more than 160 million hectares of paddy rice fields worldwide (Khanam, Kulsum & Mandal, 2025). In Kenya, rice farming is essential to food security. The country has witnessed an increase in the demand for rice over the years owing to dietary shifts and increasing population (Mano, Njagi & Otsuka, 2022). This has necessitated the growth of irrigated rice schemes including Mwea Irrigation Scheme, Ahero Irrigation Scheme (AIS), West Kano Irrigation Scheme, Perkerra Irrigation Scheme and Bunyala Irrigation Scheme. These rice growing schemes have intensified their agricultural practices owing to the rising demand. This not only constrains Kenya's finite freshwater supplies but also affects soil health and nutrient dynamics. Because of its well-established infrastructure and proximity to an active farming community, the Ahero Irrigation Research Station (AIRS), which is part of AIS, offers a strategic location for research on sustainable rice production methods.

Traditional rice growing methods have heavily relied on continuous flooding (CF). Because of their high water requirements, contribution to greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) and potential to deteriorate soil health, traditional rice farming methods are coming under increasing scrutiny (Carrijo et al., 2017). There is an urgent need to investigate irrigation techniques that maximize resource use while preserving or increasing yield because land degradation, climate variability, and limited water availability are endangering agricultural productivity. By maximizing water use and reducing adverse environmental effects, Alternate Wetting and Drying (AWD) has become a sustainable irrigation technique that may help allay these worries.

Instead of continuously submerging the rice field, the AWD irrigation method lets it dry out periodically before flooding it again. AWD has shown promise in lowering irrigation water consumption, increasing water use efficiency, and possibly improving crop productivity, nutrient dynamics, and soil microbial activity (Islam et al., 2021; Rahman et al., 2022). According to studies done in South and Southeast Asia, AWD can cut methane emissions by more than 50%, maintain or marginally increase grain yields, and reduce water use by 20–40% when compared to CF systems (Carrijo et al., 2017). Because of these advantages, AWD is positioned as a more cost-effective and environmentally friendly substitute for CF in irrigated rice systems.

The effects of AWD on rice productivity, long-term soil health (including salinity and sodicity), nutrient availability and uptake, and soil chemical characteristics are not sufficiently explored. Although research conducted in Asia has shown that AWD has a positive or neutral impact on phosphorus availability and nitrogen use efficiency, little is known about how AWD interacts with regional soil types, climate, and rice management techniques in Sub-Saharan Africa, especially in Kenya. With its clay loam soils and semi-humid climate, the AIS offers a distinctive agro-ecological setting in which the effects of switching from CF to AWD require careful consideration.

In order to develop localized irrigation and fertilization guidelines that support soil fertility and sustainable production, it is essential to underscore AWD impacts on soil health and nutrient dynamics in the soil. Furthermore, monitoring changes in grain yield and water use efficiency under the AWD and CF regimes can yield empirical data that can inform climate-smart agricultural investments, farmer training, and environmental policy in Kenya.

1.2 Ahero Irrigation Scheme

The Ahero Irrigation Scheme (AIS) is a crucial agricultural project that greatly contributes to the nation's rice production and food security. It is located in Kisumu County, Kenya, on the Kano Plains. AIS is situated in Nyando Sub-county, about 20 kilometers east of Kisumu City (Plate1.1 shows the map of AIS). It was one of the first public irrigation programs created in 1966 to increase Kenyan agricultural output (National Irrigation Authority, 2025). The Nyando River provides the scheme's irrigation water, which is then distributed throughout the fields via a pump-fed system.

Over the years, AIS has grown to approximately 4176 acres from its original 2,168 acres. The main crop grown in the scheme is rice. With 74% of production, Sindano (IR-2793 & ITA 310) is the most widely grown rice variety. Komboka (20%), aromatic varieties like Basmati-370 (5%), and hybrid varieties like Arize Tej Gold & Arize 6444 Gold (1%), are next in line (National Irrigation Authority, 2025). Over 2,000 farmers receive direct assistance from AIRS, and their operations are thought to benefit approximately 30,000 dependents (Omollo, 2022). The program has played a significant role in raising food security, creating job opportunities, and improving livelihoods in the area.

Research on crop varieties, soil management, and irrigation techniques is conducted in large part by Ahero Irrigation Research Station (AIRS), which has a close affiliation with the Kenya Agricultural and Livestock Research Organization (KALRO). Findings from the station help guide policy choices and best practices, enhancing the irrigation scheme's productivity and sustainability.

Notwithstanding its achievements, AIS still has to contend with issues like deteriorating infrastructure, volatile market prices, a lack of funding for research, and climate variability. These problems are being addressed by ongoing research, farmer training initiatives, technical support and rehabilitation projects, which promise to guarantee the scheme's durability and ongoing support of Kenya's agriculture industry.

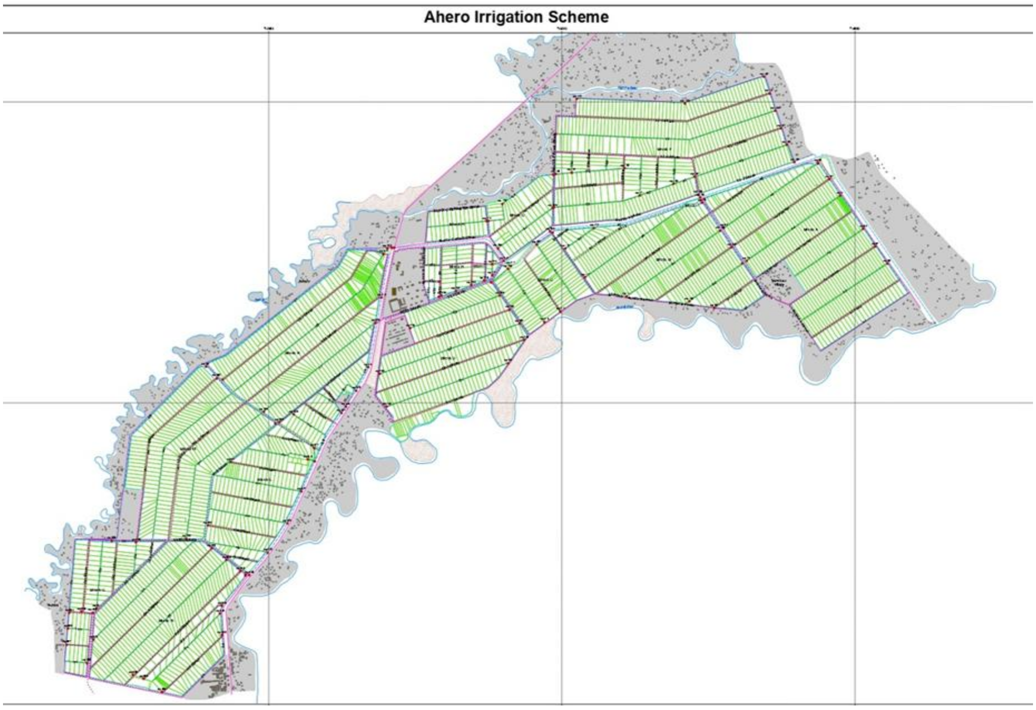


Plate 1: A Map of the Area under AIS

1.3 Problem Statement

Across the rice irrigation schemes in Kenya, including the Ahero Irrigation Scheme, rice cultivation has long been done under continuous flooding (CF) irrigation system. This approach relies on steady water supply. CF has serious agronomic and environmental problems, including excessive water use, methane emissions, soil degradation, and nutrient imbalances. AWD, on the other hand, is poised as a viable climate-smart irrigation technique that can preserve or increase rice yields while lowering greenhouse gas emissions and water consumption. The relative effects of AWD and CF on soil health, nutrient dynamics and rice productivity, particularly in Kenya's clay loam soils under extensive irrigation schemes like Ahero, are still not documented.

Notwithstanding the benefits of AWD, little is known about its possible impacts on soil chemistry and nutrient composition-all important markers of soil sustainability. The development of sustainable water management plans and evidence-based irrigation policies that can support Kenya's national climate action pledges and food security objectives is hampered by this knowledge gap. AWD and CF irrigation systems' performance in the Ahero Irrigation Scheme will thus be thoroughly assessed and compared in this study in order to ascertain their effects on soil quality, nutrient availability, and total rice grain yield. The results will offer vital information to guide policy changes, environmental preservation, and sustainable farming methods in Kenya's irrigated rice schemes.

1.4 Justification of the Study

Water scarcity, soil degradation, and climate-induced stressors are posing a growing threat to the sustainability of rice cultivation in sub-Saharan Africa. The continued adoption of CF irrigation system in Kenya's rice production schemes poses a plethora of challenges. Although CF is good at maintaining yields, it uses a lot of water and may cause unfavorable soil conditions like decreased nutrient use efficiency, acidification, salinity buildup, and anaerobic decomposition. Kenya's environmental objectives are directly jeopardized by the continued adoption of CF in paddy rice fields.

AWD has gained international recognition as a climate-smart, water-saving technology that has been shown to cut methane emissions by up to 60%, reduce water use by up to 40%, and in certain situations, preserve or increase rice yields (Islam, Sander & van Groenigen, 2021). AWD's medium to long-term effects on soil health, nutrient dynamics, and productivity under the particular clay loam soils and irrigation practices of the Ahero scheme are particularly not studied in Kenya, despite these global findings.

Critical soil chemical parameters like cation exchange capacity (CEC), total organic carbon (TOC), and micronutrient behavior under various irrigation regimes have frequently been overlooked in favor of narrowly focusing on water savings or yield outcomes in the majority of prior studies. Additionally, little is known about how AWD influences soil and water interactions over time, particularly at different stages of rice growth (such as panicle initiation and post-harvest). In Kenya and other agro-ecological zones, this gap presents a serious obstacle to the development of evidence-based policies and the expansion of AWD.

As a result, this study offers a methodical, multidisciplinary comparison of AWD and CF in terms of soil chemical health, nutrient availability and rice productivity over several growing stages. In addition to gathering empirical data, it will produce useful suggestions for managing irrigation, preserving soil fertility, and promoting sustainable rice intensification in East Africa.

The study is uniquely positioned to influence Kenya's climate adaptation strategy, investments in environmentally sustainable rice irrigation technologies, and agricultural water management policies (under the Water Act and Irrigation Act) by addressing both scientific and policy-relevant questions. Additionally, under changing climatic conditions, it will promote academic advancement in soil-rice environmental systems.

1.5 Hypothesis

1.5.1 H_0 (Null Hypothesis):

There is no significant difference between AWD and CF irrigation systems in terms of their effects on soil chemistry, nutrient dynamics and rice yield in the Ahero Irrigation Scheme.

1.6 Objectives

1.6.1 Main Objective

To compare the effects of AWD and CF irrigation regimes on soil chemical properties, nutrient dynamics and rice yield performance, with a view to evaluating their implications for soil health and sustainable rice production in the Ahero Irrigation Scheme.

1.6.2 Specific Objectives

1. To evaluate the effects of AWD and CF on soil chemistry in rice fields during crop growth.
2. To assess changes in N, P, K, S, ca, mg, cu, Fe and zn bioavailability in rice fields under AWD and CF irrigation regimes.
3. To establish the implications of AWD on soil salinity/sodicity and soil health parameters in irrigated rice systems.
4. To analyze the influence of AWD on rice yield at Ahero Irrigation Scheme.

1.7 Research Questions

1. How do AWD and CF irrigation systems influence key soil chemical properties in rice fields at panicle initiation and post-harvest stages?
2. What differences in nutrient availability occur under AWD compared to CF throughout the rice growth cycle?
3. What are the effects of AWD on soil salinity, sodicity and overall soil health in irrigated rice fields?
4. How does AWD affect rice grain yield compared to CF in the Ahero Irrigation Scheme?

1.8 Scope of the Study

The application of AWD in rice farming within AIS in Kisumu County, Kenya was the focus of this study. The study evaluated soil health, nutrient dynamics and rice yield in an experimental rice field at AIRS. The study was carried out over the April-September 2025 growing season using test plots under actual block rotation irrigation schedules. Despite the project's local scope, the results should influence practice and policy in other regional and Kenyan irrigation projects.

1.9 Conceptual Framework

1.9.1 Conceptual Focus and Relationships

This study investigated the effects of two irrigation techniques, AWD and CF, on soil chemistry, nutrient dynamics, rice yield and soil health. The irrigation method affects soil moisture and redox conditions, which in turn affect the dynamics of soil organic carbon (through aerobic/anaerobic decomposition), nutrient transformations (such as nitrogen mineralization and phosphorus fixation), soil pH (which further regulates nutrient availability), and sodium accumulation or leaching (which affects sodicity). Together, these modifications have an impact on rice grain yield, soil fertility and health, and the bioavailability of vital nutrients to rice plants.

In this research study, the conceptual framework is crucial. It first illustrates how AWD and CF irrigation systems affect soil health and rice yield. Secondly, it draws attention to the relationships that exist between crop performance and soil chemistry. Thirdly, it encourages a multidisciplinary strategy that connects environmental sustainability, agronomy, and soil science.

1.9.2 Main Parameters and Variables

I. Independent Variables
    Irrigation Regimes: AWD (treatment) and CF (control)
II. Intervening Variables
    1. Soil texture and type (clay loam)
    2. Environmental conditions (rainfall, temperature)
    3. Fertilizer management
    4. Rice variety used
III. Dependent Variables

6.1 Soil Chemistry
    a) pH
    b) Cation Exchange Capacity (CEC)
    c) Organic Carbon
6.2 Nutrient dynamics
    a) N, P, K, S
    b) Ca, Mg
    c) Fe, Zn, Cu
6.3 Soil Salinity/Sodicity
    a) Sodium levels
    b) Cation Exchange Capacity
6.4 Agronomic Performance
    a) Rice yield
    b) Number of tillers, grain weight, grain-filling efficiency

1.9.3 Visual Representation of the Conceptual Framework

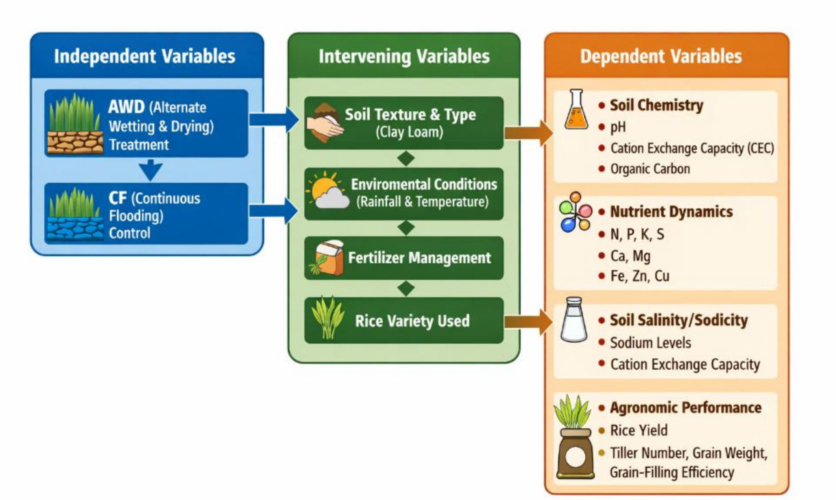


Plate 2: A Flowchart Showing the Conceptual Framework for the Research Study

II. LITERATURE REVIEW

2.1 Rice Cultivation

Rice is one of the most popular cereals in the world. It is a semi-aquatic or aquatic crop that needs a lot of water to thrive. Therefore, rice farming prefers soils with a high water-holding capacity, such as silt clay loam, silt clay, and clay (Akuatik et al., 2016). In terms of water productivity, rice production is significantly influenced by soil characteristics including the percolation rate, pH, salinity, and soil organic matter (SOM) contents (Dou et al., 2016). Because they have a higher rate of percolation and thus leach the necessary nutrients (including additional fertilizers), light-textured soils are typically less productive than soils with high clay content.

Rice farming is influenced by several environmental and associated factors. Due to the heavy reliance on water for rice cultivation, flooding and drought are both significant limiting factors (Lavane et al., 2023). Significant yield losses can result from drought stress, particularly during the flowering and reproductive stages (Bhandari et al., 2023; Ishimaru et al., 2022; Gui et al., 2022). On the other hand, flooding results in anaerobic conditions which cause waterlogging problems, and methane emissions (Rupngam & Messiga, 2024). Temperature is another crucial environmental parameter in rice farming. Variations in temperature can affect the overall performance of rice crop. High temperatures can have a detrimental effect on yield, especially when the grain is filling (Lu et al., 2025; Shimoyanagi, Abo & Shiotsu, 2021; song et al., 2022). Additionally, in the early stages, low temperatures can impede growth and development (Abbas & Mayo, 2021). Furthermore, soil quality is crucial for rice cultivation; in addition to fertility, soil salinity can be a limiting factor, especially in coastal regions or where irrigation water is saline (Rodríguez Coca et al., 2023).

2.2 Convectional Rice Cultivation

The CF irrigation system has long been used for rice cultivation. In CF, a consistent water depth (usually 3–10 cm) in the rice field is maintained after the 5-leaf stage and continuing until close to harvest (Cai et al., 2025). CF is especially prevalent in the ecology of lowland rice. In order to maintain the field submerged for a sizable amount of the growing season, the water level is frequently raised gradually as the plants develop. The rice fields are maintained flooded until very close to the harvest, about 7-10 days prior. CF facilitates soil puddling, which creates a low-permeability layer that conserves water. It also supports transplanting, weed control and nutrient availability (Cowan et al., 2021). CF continues to be the standard irrigation technique in rice paddies around the world. Additionally, as shown in numerous areas where rice production flourishes under sustained flood regimes, CF has proven its capacity to maintain high rice yields (Wu et al., 2017).

Irrigated rice farming is linked to a number of serious soil and water-related environmental problems. These issues have wider ramifications for food security, biodiversity, greenhouse gas emissions, and resource efficiency in addition to endangering the sustainability of rice farming systems. Rice is arguably one of the most water-intensive crops; under continuous flooding (CF) techniques, one kilogram of rice requires 2,000 to 5,000 liters of water (Bouman & Tuong, 2001). Surendran, Raja, Jayakumar and Subramoniam (2021) estimate that an average of 2500 liters of water is necessary for production of one kilogram of rice. Rice is traditionally grown using CF, which uses a lot of freshwater. Water tables are lowered as a result of excessive water extraction from aquifers and rivers. Additionally, it raises the possibility of water disputes between users in places where demands are conflicting. Additionally, communities and ecosystems downstream have less access to water.

Salt buildup in the root zone can result from prolonged irrigation, particularly in soils with poor drainage, or in arid or semi-arid environments (Qadir, et al., 2007). This issue could be made worse by improper drainage or rising groundwater tables. Because of poor soil structure and osmotic stress on plants, this can lead to soil degradation and ultimately result into decreased productivity (Shrivastava & Kumar, 2014). Additionally, it may cause nutrient uptake to be inhibited, particularly in sodic soils. Furthermore, salinity and sodicity are attributable to loss of the functionality and diversity of soil microbes (Gao et al., 2022; Zhang et al., 2024).

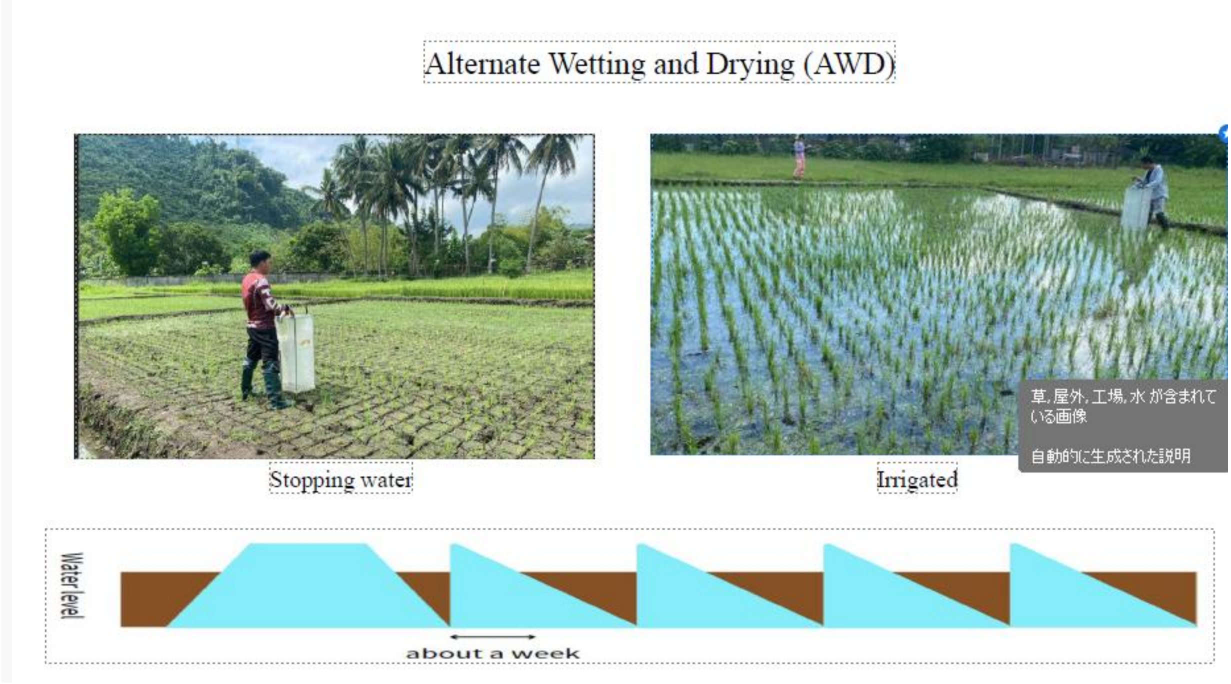
Intensified rice farming can also pose a risk to the environment. Characterized by high fertilizer input, rice intensification is a major contributor to leaching of nutrients, acidification of the soil, a decrease in organic matter, and even changes to the soil structure are likely (Ladha et al., 2009). The consequences include decreased crop resilience, decreased long-term soil fertility, and increased reliance on outside inputs. Additionally, waterlogging affects the stability of some micronutrients in the soil. The solubility and availability of micronutrients are impacted by the anaerobic conditions that result from flooded rice paddies (Fageria, Baligar & Li, 2008). Increased availability of iron and manganese in particular can occasionally result in toxicity (Zahra et al., 2021; Dey et al., 2023). Precipitation or competition may result in a reduction in the availability of zinc, copper, and molybdenum.

Methane production in rice fields is also an important environmental concern. CF is a significant source of methane, a powerful greenhouse gas. Waterlogged soils promote the anaerobic conditions necessary for methanogenesis to occur (Linquist et al., 2012). Because of this, growing rice the conventional way is one of the main agricultural activities that contribute to greenhouse gas emissions worldwide.

2.3 Alternate Wetting and Drying

In AWD, paddy fields are periodically flooded as a water management technique. A period of flooding is followed by draining of water, falling 10 to 15 cm below the soil surface before re-irrigating (See Plate 3). Periods of aerobic conditions brought about by this cyclical drying and rewetting promote methanotrophic bacteria, which convert methane back into carbon dioxide, and prevent the growth of methanogenic microorganisms (Conrad, 2007). The use of AWD has been demonstrated to improve rice plant root development and nutrient uptake (Bouman et al., 2007) and results in significant water savings.

In conventional flooding, which is frequently used in rice farming, the fields are continuously submerged to a depth of 3 to 10 cm. By fostering an anaerobic environment in the soil, this technique encourages the activity of methanogenic archaea, which produce methane as a byproduct of the breakdown of organic matter (Li et al., 2021). Methane contributes to global warming when it leaks into the atmosphere. By letting the soil dry out occasionally, AWD shortens the time that anaerobic conditions persist, which lowers the amount of methane produced. This approach is a sustainable substitute for ongoing flooding since it reduces methane emissions while also improving water use efficiency. According to Gitonga et al. (2019), AWD in the Mwea Irrigation Scheme in Kenya saw water savings of 26–45% while yield productivity increased by up to 78%, depending on the soil type. These results highlight the potential of AWD to improve rice cultivation's water use efficiency (Plate 4 compares CF with AWD).



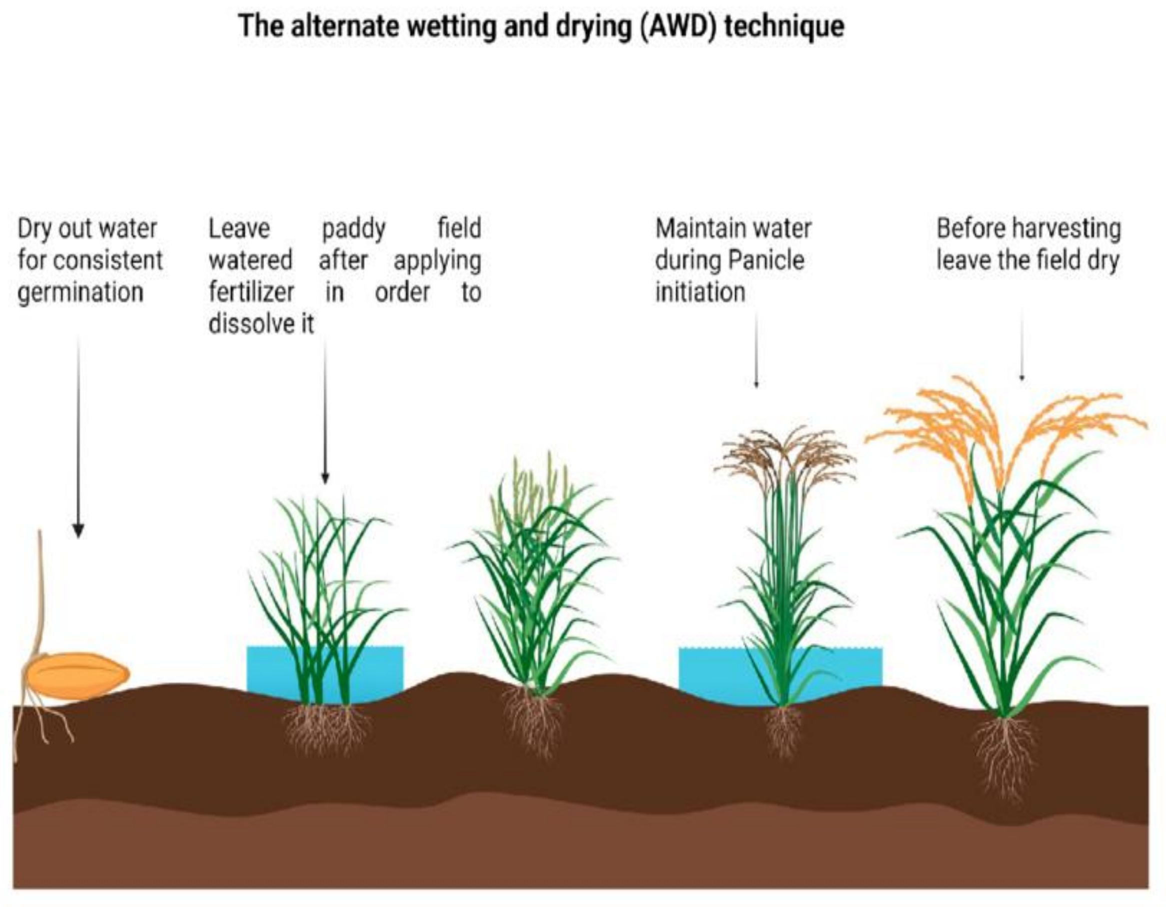


Plate 3: The concept of AWD

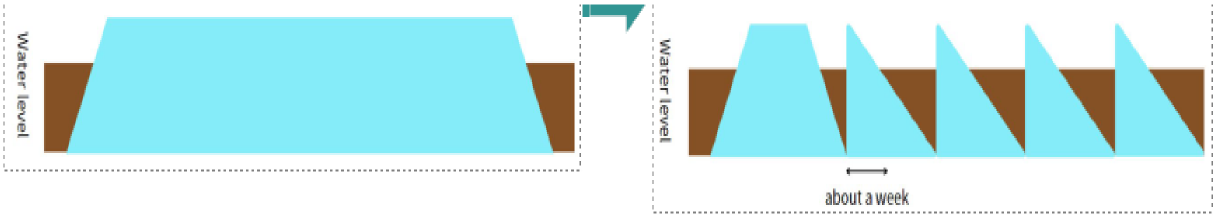


Plate 4: An illustration of how AWD compare to conventional rice management (CF)

2.4 Effects of AWD on Soil Chemical Properties and Soil Health

AWD has the potential of altering the chemical properties of the soil positively and even negatively. For sustainable agriculture, it is essential to comprehend the interplay between chemical characteristics of the soil and irrigation systems. Soil chemistry has a significant impact on crop productivity and nutrient availability. Islam, Price and Hallett (2024) observe that soil properties have a role in improving the utilization of resources within the soil by rice plants. AWD may have an impact on the chemical characteristics of the soil. According to He et al., (2022), AWD's sporadic drying periods improve soil aeration, which raise microbial activity and enhance nutrient cycling. Furthermore, it has also been linked to improved nutrient retention through increased soil organic carbon and cation exchange capacity (Haque et al., 2021). To preserve soil health, careful management is required because the shifting redox conditions under AWD may also affect the availability and solubility of specific nutrients (Majumdar et al., 2023).

2.4.1 Soil pH

Considering that AWD procedures alternate between aerobic and anaerobic conditions, soil pH changes are inevitable. Increased oxygen availability during drying stages may cause reduced compounds to oxidize, which could raise the pH of the soil. Re-flooding, on the other hand, can produce anaerobic conditions that reduce iron and manganese oxides, potentially lowering pH levels (Majumdar et al., 2023). Adhikary et al. (2023) found that AWD decreased soil-available phosphorus, mainly because of higher microbial biomass that immobilized phosphorus and lower ferrous iron content, which altered pH and nutrient dynamics.

2.4.2 Cation Exchange Capacity

An important measure of soil fertility is Cation Exchange Capacity (CEC). It represents the soil's capacity to store and exchange cations. By altering the amount of organic matter in the soil and the microbial activity, AWD can have an impact on CEC. According to Haque et al. (2021), AWD improves soil CEC, total carbon, and nitrogen levels, particularly when applied in conjunction with biochar. In the study, the application of biochar was found to improve the physicochemical attributes of the soil resulting into improved nutrient availability and retention.

2.4.3 Availability of Macronutrients

AWD may also influence nutrients availability and uptake. These nutrient dynamics have far-reaching effects on the overall plant health and by extension the environment. More nitrogen may be available for uptake by plants considering that AWD limits denitrification and volatilization. This implies that AWD may reduce nitrogen losses. The aerobic conditions during the AWD drying phases are critical to these processes. This would improve rice plants' uptake and efficiency in using nitrogen. On the other hand, because of the increased microbial biomass and decreased ferrous iron content, AWD may cause phosphorus to become immobilized, which could decrease its availability (Adhikary et al., 2023). Redox conditions affect phosphorus availability. By increasing soil aeration and microbial activity, AWD may increase potassium availability by making it easier for potassium to be released from soil minerals.

2.4.4 Soil Organic Carbon

A vital component of soil health is soil organic carbon (SOC). It affects water retention, nutrient availability, overall soil fertility and detoxification of harmful substances in the soil (Gerke, 2022). AWD is important in regulating SOC dynamics in rice cultivation. AWD encourages microbial activity and soil aeration, in contrast to CF. In particular, AWD's drying phase accelerates organic matter decomposition, improves soil aeration and aerobic microbial activity, which can possibly result in SOC loss (Yadav, Mishra & Maurya, 2025). Subsequently, SOC accumulation is made possible by the anaerobic conditions created by re-flooding, which slows down decomposition. It has been demonstrated that adding organic amendments, like compost and biochar, along with AWD raises SOC levels (Haque et al., 2021). By improving soil structure and adding more carbon sources, these amendments increase SOC sequestration.

Variations in SOC levels affect rice farming in a number of ways. First, it plays a crucial role in the cycling of nutrients, especially phosphorus and nitrogen (Feng et al., 2022). Increased SOC levels support improved plant growth and yield by improving nutrient availability. Second, higher SOC helps to improve soil structure and water-holding capacity (Acin et al., 2013), both of which are important for rice plants, particularly during the drying phases of AWD. Third, methanogenic bacteria's ability to produce methane from the soil is influenced by variations in SOC dynamics and redox conditions (Dahlgreen & Parr, 2024).

2.4.5 Salinity and Sodicity

In areas with high rates of evaporation, AWD can affect the salinity and sodicity of the soil. While re-flooding can promote salt leaching, drying phases may cause salt to accumulate at the soil's surface (Devkota, Devkota, Rezaei & Oosterbaan, 2022). In order to avoid possible soil degradation brought on by salinity and sodicity problems, proper management of AWD is essential. The buildup of soluble salts in the soil, such as sodium chloride is what results into soil salinity (Ismayilov et al., 2021). This can hinder plant water uptake, resulting in osmotic stress and subsequently lower crop yields (Balasubramaniam, Shen, Esmaeili & Zhang, 2023). Additionally, it may lead to salt toxicity and occasionally alter the structure of the soil (Chele et al., 2021). Sodicity is characterized by high concentrations of exchangeable sodium ions in the soil, which easily weakens the soil structure, decrease its permeability, and make salinity problems worse. Additionally, it causes surface crusting, decreased aeration, pore clogging, and soil particle dispersion (Ran et al., 2023; Taghizadehghasab, Safadoust & Mosaddeghi, 2021).

In contrast to AWD, CF keeps a steady layer of water on top of the soil, which can affect salinity and sodicity in a number of ways. Salinity and sodicity can be reduced through salt leaching. Surface salinity is lowered by the continuous water layer which promotes salt leaching outside of the root zone. However, long-term flooding can cause waterlogging, which can interfere with microbial activity and soil aeration, potentially influencing soil structure and nutrient availability. Sodicity can be rampant in regions where irrigation water is high in sodium. In these situations, CF may help sodium ions build up, which over time may increase sodicity and deteriorate soil structure.

2.4.6 Availability of Micronutrients

For rice to grow and develop in a healthy manner, micronutrients like iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), and others are essential. According to Song et al. (2021), soil water management practices have a major impact on availability and uptake of micronutrients. During the drying phases of AWD, ferrous iron oxidizes to ferric iron, which would decrease its availability and solubility for plants. According to Adhikary et al. (2023), under anaerobic conditions, ferric iron (Fe^{3+}) is reduced to the more soluble ferrous iron (Fe^{2+}), thereby increasing its availability for uptake by rice plants. However, excessive Fe^{2+} can lead to toxicity in rice plants. Under AWD, the pH and redox conditions of the soil affect the availability of Zn and Cu (Haque et al., 2021). In some cases, CF can lead to the formation of insoluble sulfide complexes, which results into unavailability of Zn and Cu to rice plants.

2.5 Effects of AWD on Rice Yield

Empirical research has largely addressed concerns regarding yield loss in AWD. Research conducted in South and Southeast Asia indicates that improved root development and nutrient uptake under AWD result in yields that are either maintained or marginally increased (Bouman & Tuong, 2001; Belder et al., 2004; Sander, Samson & Buresh, 2017; Mishra et al., 2017; Islam, Sander & van Groenigen, 2021; Hoang et al., 2023). In a study involving on-farm trials in Burkina Faso, West Africa, AWD resulted into an increase in grain yield by 6% and irrigation water productivity by 64%. At the same time, irrigation water input was reduced by 23% during the wet season and 32% during the dry season (Johnson et al., 2024). Further, the impact of AWD on rice yields has shown to vary according to the level of implementation. According to a meta-analysis of 56 studies, mild AWD (soil water potential ≥ −20 kPa or water level not falling below 15 cm from the surface) reduced water use by 23% without significantly lowering yield. On the contrary, severe AWD (soils dried more than -20 kPa, particularly in soils with a pH of 7 or less than 1% carbon content) resulted into a drop in yields by 22.6% compared to CF (Carrijo, Lundy & Linquist, 2017). According to a study done in the United States at 19 on-farm locations throughout the Mississippi Delta, AWD maintained or increased rice grain yield by up to 11% compared to CF. Depending on pumping costs, the increased net returns ranged from \$119 to \$238 per hectare (Atwill et al., 2020)

2.6 Sodium Adsorption Ratio and Exchangeable Sodium Percentage

The sodium hazard in soil or irrigation water is gauged by the sodium adsorption ratio (SAR). Greater sodium dominance is indicated by higher SAR, which causes clay dispersion and decreased soil permeability. SAR < 3 is generally regarded as safe, SAR 3–9 as manageable, SAR 10–18 as moderate hazard, and SAR > 18 as high risk for sodicity (Bhat et al., 2018). On the other hand, the percentage of sodium ions adsorbed onto soil Cation Exchange Sites (CEC) constitutes the Exchangeable Sodium Percentage (ESP). It gives a clear indication of sodicity risk in the soil. Low risk values are less than 15%, moderate risk values are between 15% and 40%, and high risk values are greater than 40% (Omar et al., 2024).

Soil and water quality can be inferred from both SAR and ESP measurements. Destabilized soil aggregates, pore collapse, decreased hydraulic conductivity, and surface crusting are all consequences of high ESP (Chemura et al., 2014). Rice paddies are significantly impacted by soils with elevated SAR/ESP because they have low infiltration, a soggy surface, and poor aeration (Rhoades, Kandiah & Mashali, 2012). Even after remediation, cycles of salinity and sodicity can result in an irreversible loss of soil permeability (Adeyemo et al., 2022).

2.7 National and International Environmental Codes and Governance

2.7.1 Environmental Management and Coordination Act (EMCA)

Kenya's main environmental law is the Environmental Management and Coordination Act (EMCA) Cap. 387. The law, which is enforced by the National Environment Management Authority (NEMA), lays out numerous obligations and protections for environmental coordination and management. It provides procedures for safeguarding and conserving the environment, including water and soils. It includes provisions for irrigation project audits and Environmental Impact Assessments (EIAs), among others (The National Council for Law Reporting, 2022). An environmental audit may involve keeping an eye on the water and soil quality in irrigation systems. Additionally, the law protects aquatic ecosystems from factors like salinization.

2.7.2 The Water (Amendment) Act (2024)

Guidelines for the conservation, management, and sustainable use of water resources are provided by the Water Act of 2016 amended in 2024. It requires the Water Resources Authority (WRA) to control the use and abstraction of water. In order to avoid over-abstraction and encourage water use efficiency, it also supports the adoption of efficient technologies.

2.7.3 Agricultural Sector Transformation and Growth Strategy (ASTGS, 2019–2029)

The goal of the ASTGS is to revolutionize Kenya's agricultural sector. It gives soil fertility management, climate-smart agriculture, and sustainable irrigation top priority. Additionally, it provides for promotion of productivity with less impact on the environment. It also advocates for data-driven irrigation techniques (Ministry of Agriculture, Livestock, Fisheries and Irrigation, 2019).

2.7.4 National Irrigation Policy (2021) and Irrigation Act (2019)

The National Irrigation Authority (NIA) is a body established by the Irrigation Act with the following mandates: to develop and improve irrigation infrastructure for national or public schemes; to provide irrigation support services to private medium and smallholder schemes in consultation and cooperation with county governments and other stakeholders; and to provide technical advisory services to irrigation schemes in the areas of design, construction supervision, administration, operation, and maintenance under suitable modalities, including agency contracts. The National Irrigation Policy and the Act both encourage the creation of effective, climate-smart irrigation techniques. Additionally, they stress environmental preservation, equity, and stakeholder participation in irrigation projects.

2.7.5 Paris Agreement (2015)

The implementation of AWD aligns with Article 2 goals on climate adaptation and mitigation in the Paris Agreement. Kenya is one of the signatories to this multilateral agreement. The agreement was signed and ratified in 2016. It supports climate-resilient agriculture and sustainable water management.

2.7.6 UN Sustainable Development Goals (SDGs)

Various SDGs directly support the need for healthy soils, efficient water use, biodiversity and increased agricultural productivity. A UN initiative, the SDGs are a global call to action to eradicate poverty, safeguard the environment, and guarantee that everyone lives in peace and prosperity by 2030. Zero hunger is the focus of SDG 2. This strategic objective is directly addressed by mechanisms such as increased rice productivity. SDG 6 promotes the need for clean water and sanitation. Thus, water efficiency is given top priority. Additionally, SDG 15 calls for maintaining biodiversity and soil health.

III. MATERIALS AND METHODS

3.1 Study Site

The study took place at AIRS, which is part of AIS located in Muhoroni Sub-county in Kisumu County, Kenya. The scheme is approximately 1168 m above the sea level. It lies at 0° 08′ 03″ S, 34° 58′ 07″ E. The area receives an average annual rainfall of 1,200 mm, which is spread across two rainy seasons (March–May and October–December). It is highly humid (averaging 65.5%) and experiences average temperatures between 22°C and 30°C. The dominant soil type in the area is clay loam which is characterized by moderate fertility and water retention capacity.

3.2 Experimental Design

The study involved a field experiment comparing two treatments (comparative experimental design);

- Treatment: AWD
- Control: CF

Two plots of equal size, each measuring roughly 0.25 acres, were created and divided by a bund. To ensure that spatial variability and redox-driven heterogeneity were taken into account, specific sites were considered based on stratified systematic random sampling.

The two test plots were prepared uniformly, and rice variety IR -2793-80-01 planted under identical agronomic conditions. Each the plots were treated as independent experimental units.

3.3 Soil Sampling

3.3.1 Sampling Points

Soil samples were drawn from 25 sampling points per plot. The 25 points were achieved through a subdivision of the plot into 25 equal cells each measuring about 40m^2.This approach ensured representativeness, uniform coverage and spatial distribution in each plot. For each of the sampling points, one soil subsample was taken, making them 25 subsamples. The subsamples for each plot were used in preparing one composite sample.

3.3.2 Sampling Frequency

In order to correspond with important phenological stages, soil samples were taken three times during the cropping season: first, during pre-planting. This is done prior to transplantation of the seedlings, the goal being to determine the baseline soil conditions. This was completed a week prior to transplanting and following land preparation. The second sampling took place during the mid-season, or panicle initiation (PI) stage. Capturing nutrient availability and chemical changes during a critical growth stage, when nutrient uptake peaks. The last soil sampling was done after the crop was harvested. The goal of the final sampling is to evaluate the irrigation treatment's cumulative effects on soil quality and residual nutrient content.

3.3.3 Soil Sampling and Preparation

Soil samples were collected using a soil auger at a depth of 0-20 cm from the soil surface at three critical growth stages across the rice growing season;

a) Pre-planting (Baseline); the first samples were collected from the freshly prepared plot before subdivision.
b) Panicle initiation; a set of soil samples (for AWD and CF) were collected during the panicle initiation (PI) stage.
c) Post-harvest; after the crop is harvested more samples were drawn from both AWD and CF plots

The soil sampling auger (made of stainless steel) was thoroughly cleaned prior to sampling and between sampling points with 70% ethanol. On the other hand, all glassware and plastic sampling containers were soaked in 10% nitric acid, rinsed thoroughly with deionized water, and dried before use to avoid any contamination.

3.3.4 Sampling Procedures

At each sampling time, composite soil samples were collected from a 0–20 cm depth using an auger. To ensure they constitute a representative sample, the sub-samples were thoroughly mixed distinctively for each plot. Each of the two samples per sampling time (approximately 500 g) was packaged and labeled appropriately.

3.3.5 Pre-treatment of Soil Samples

a) The two representative samples were air-dried in the shade for about two hours
b) In the course of air-drying, all foreign materials in the soil, including stones, roots and large debris were removed.
c) The samples were then sieved through a 2 mm mesh and the sieved samples stored in clean plastic bags ready for laboratory analysis

3.5 Rice Yield Determination

a) Rice was harvested from 1 m × 1 m quadrats selected from three locations for each of the test plots; near the feeder canal, at the middle and near the drain canal.
b) From each of the three sampling locations (feeder, middle and drain), three quadrats were randomly selected.
c) Subsequently, the number of rice hills per quadrat was recorded
d) Following sun-drying to about 12% moisture content, grain yield was measured in grams per square meter.

3.6 Analytical Procedures

3.6.1 Soil Analysis

Table 1: Different Soil Parameters and the Methods used in Analysis

Parameter	**Method**
pH	1:2.5 soil-water suspension (Glass electrode)
EC	Conductivity meter
Organic carbon	Walkley-Black wet oxidation
Nitrogen	Kjeldahl digestion
Phosphorous	Bray I method
Exchangeable K, Ca, Mg, Na	Ammonium acetate extraction + AAS
Cation Exchange Capacity (CEC)	Ammonium acetate method
Sulphur	Turbidimetry
Micronutrients (Fe, Zn, Cu)	DTPA extraction + AAS

3.7 Hypothesis Testing

Hypothesis testing was done by comparing between AWD and CF values across the diverse parameters being tested.

3.8 Overall Data Analysis and Presentation

Descriptive statistics was used in summarizing the data. Further data analysis was done using a two-way ANOVA and t-tests. Tables and graphs were used in data representation.

IV. RESULTS

This chapter offers a comprehensive examination of soil chemistry, nutrient dynamics, soil health indicators, and rice yield performance under AWD and CF irrigation systems at the AIS. The study was conducted during the May–September 2025 rice growing season. The analyses were performed in accordance with the research objectives and the articulated null hypothesis (H_0). Trends were summarized using descriptive statistics (means and percentage changes across growth stages). On the other hand, two-way ANOVA coupled with Welch's t-tests were used in underscoring the difference between AWD and CF on the overall rice grain yield.

Z-scores (±3) and boxplot inspection were used for outlier screening. For the soil chemistry datasets, there were no extreme outliers. However, one CF feeder observation with a disproportionately high post-winnowing grain weight in relation to hill density was found to be a mild outlier in the yield data, but it was kept because its z-score was less than ±3. Sensitivity analysis that excluded this point revealed no discernible shift in the findings.

4.1 Soil Chemistry

4.1.1 Soil pH

Table 2 summarizes the findings of the pH for the AWD and CF rice fields across the growing season. The baseline pH was 5.47, which is described as strongly acidic.

Table 2: pH Data across the Rice Growing Season at AIRS

Sampling	Date	Crop Stage	AWD	CF	Replication
1	April 10, 2025	Pre-panting (baseline)	5.47	5.47	Single composite sample
2	August 5, 2025	Panicle initiation	5.29	5.84	One composite sample for each treatment
3	September 11, 2025	Post-harvest	5.74	6.04	One composite sample for each treatment

In view of the above findings, AWD plots experienced a decline in pH relative to baseline at the panicle initiation stage. On the other hand, the CF plots experienced a marked increase in pH relative to baseline. The absolute pH difference between AWD and CF at this stage was 0.55 units, which is agronomically meaningful in acidic soils.

After harvesting, the pH in both treatments showed recovery, in which case the CF maintained a consistently higher pH than AWD. The AWD-CF difference narrowed to 0.30 pH units post-harvest.

The pH trajectory across the growing season for both AWD and CF depicted a similar pattern though some notable differences were observed. For AWD, the trend showed initial acidification during crop growth and subsequent partial recovery post-harvest. The net change from baseline was +0.27, a pattern that is consistent with periodic soil oxidation during drying phases, nitrification and organic matter mineralization producing H^+ ions, and re-wetting after harvest moderating acidity. In the case of CF, progressive alkalinisation across the season resulted in net change from baseline of +0.57, depicting the effects of sustained anaerobic conditions. A careful look at the data shows that the greatest divergence took place during active crop growth, a period in which irrigation regimes exert the strongest redox control on soil chemistry.

The size and consistency of the observed variations imply that irrigation regime had a significant impact on soil pH dynamics throughout the rice growing season, even though the lack of replication precluded formal statistical testing.

4.1.2 Soil Cation Exchange Capacity

The field baseline was 12.00 meq/100 g, a moderate to adequate CEC, typical of clay loam soils. It is a reflection of the inherent charge characteristics of clay minerals and organic matter prior to irrigation treatment effects. At panicle initiation stage, both AWD and CF showed a decline in CEC relative to the baseline. However, the reduction was more pronounced under AWD. CF maintained a slightly higher CEC than AWD (difference = 0.80 meq/100 g). Post-harvest, a substantial increase in CEC occurred in both treatments with CF maintaining a marginally higher CEC than AWD (difference = 0.35 meq/100 g). Both values exceed the baseline, indicating a net seasonal gain in exchange capacity. Additionally, CF consistently maintained slightly higher CEC values, suggesting a moderating effect of prolonged anaerobic conditions on exchange site preservation. Table 3 below shows the net change in CEC across the treatments.

Table 3: Net Change in CEC across the Season for AWD and CF Regimes

Stage	AWD	CF	CF – AWD
Baseline	12.00	12.00	0.00
Panicle initiation	9.80	10.60	**+0.80**
Post-harvest	16.50	16.85	**+0.35**

4.2 Soil Health Assessment

4.2.1 Total Organic Carbon Dynamics

The following table (4) shows the TOC findings across the growing season.

Table 4: TOC Data across the Season at AIRS

Sampling	Date	Crop stage	AWD (%)	CF (%)
1	10/4/2025	Pre-planting	1.90	1.90
2	5/8/2025	Panicle initiation	2.70	3.10
3	11/9/2025	Post-harvest	0.30	0.29

After the land preparation, the soil entered the experiment with low organic carbon, below the recommended threshold (≈2.66%) for clay loam soils. This is likely a reflection of long-term cultivation, low residue return, high mineralisation rates typical of tropical agroecosystems. The ramifications of this low baseline TOC includes constrains on buffering capacity, nutrient retention, and microbial resilience.

At the panicle initiation stage, there was a positive TOC change from the baseline (shown in Figure 1).

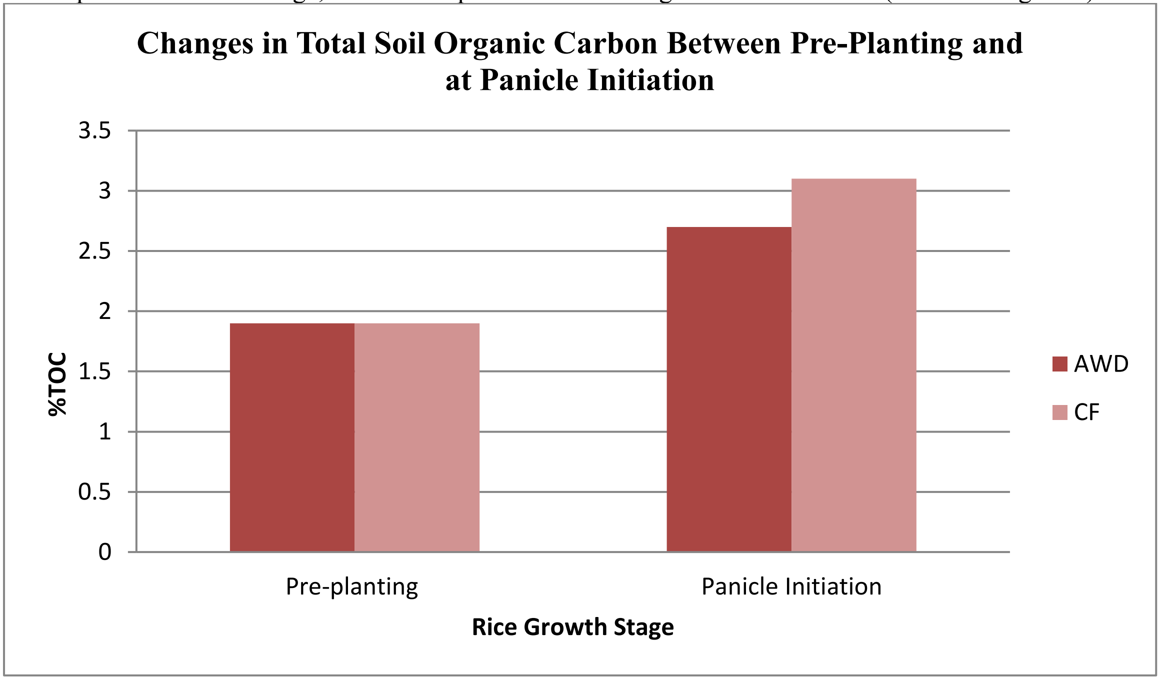


Figure 1: Changes in total soil organic carbon between pre-planting and panicle initiation

There was an observed increase in TOC during the growing phase. This can best be explained by root-derived carbon inputs. Rhizodeposition is one of the potential ways of carbon build-up in the soil via root exudates, sloughed cells and mucilage. Furthermore, there occurs rapid root turnover during vegetative growth. There is suppressed decomposition under flooding, something that can result into greater retention of labile carbon fractions in the case of CF. For AWD, periodic soil aeration accelerates oxidation, resulting into greater mineralisation of organic inputs thereby resulting into lower TOC accumulation relative to CF.

For the post-harvesting sampling, TOC declined sharply and dramatically under both irrigation regimes. The post-harvest TOC values were extremely low, representing about ~84–91% reduction relative to panicle initiation TOC. This was also a net decline relative to the baseline (Figure 2)

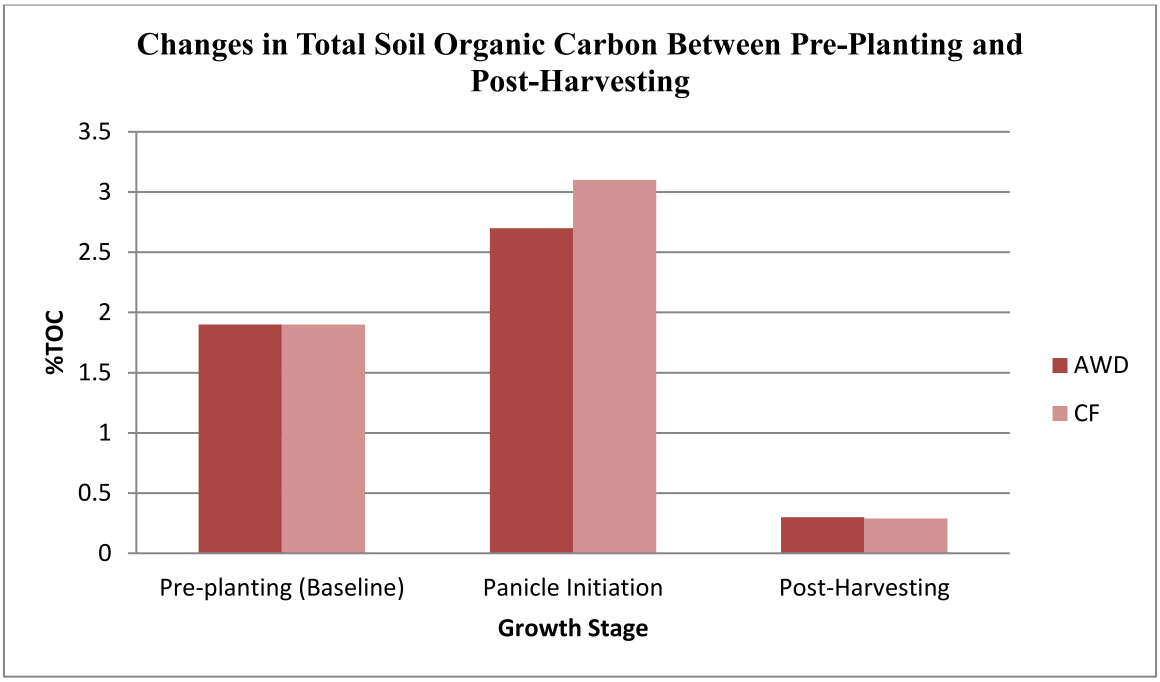


Figure 2: Changes in soil carbon between pre-planting and post-harvesting

The findings point to a severe post-harvest TOC depletion. This is likely a combination of factors including rapid mineralisation of labile carbon and priming effects. Despite higher TOC under CF during growth, both treatments converged to similarly low TOC after harvest, this was predominantly because the two fields were subjected to nearly similar conditions just before harvesting and post-harvest. Therefore, neither irrigation regime prevents post-harvest carbon collapse.

4.2.2 Salinity and sodicity

The dataset comprises of important indicators to the levels of salinity and sodicity in the soil; the exchangeable Na^+ (meq%), trends in Ca^{2+}, changes in CEC as well as the soil texture (clay loam). These parameters allows for robust qualitative and semi-quantitative inference. Table 5 below shows the changes in these critical parameters across the irrigation regimes throughout the season.

Table 5: Changes in Exchangeable Sodium, Calcium and CEC at AIRS

Parameter	AWD	CF
Exchangeable sodium (meq%)	Pre-planting: 3.92 Panicle Initiation:3.21 Post-harvest: 3.20	Pre-planting: 3.92 Panicle Initiation: 2.04 Post-harvest: 2.02
Cation exchange capacity (meq/100g)	Pre-planting: 12.0 Panicle Initiation: 9.80 Post-harvest: 16.50	Pre-planting: 12.0 Panicle Initiation:10.6 Post-harvest: 16.85
Calcium (meq%)	Pre-planting: 1.81 Panicle Initiation: 2.40 Post-harvest: 3.59	Pre-planting: 1.81 Panicle Initiation: 4.21 Post-harvest: 7.40

At baseline, exchangeable sodium levels showed a moderate to high risk of sodicity, with Na^+ concentrations above the ideal parameter limits for clay loam soils (0.00-2.00 meq%). Both irrigation regimes decreased exchangeable sodium during crop growth, but the reduction was significantly larger under continuous flooding. In contrast to 3.21 meq% under AWD, Na^+ decreased to 2.04 meq% under CF at panicle initiation, indicating improved cation exchange and leaching processes under prolonged flooding. While CF maintained near-threshold Na^+ levels after harvest, AWD caused sodium levels to rebound. The combined sodium, calcium, and CEC data show that continuous flooding was more successful than AWD in reducing the risk of sodicity throughout the rice growing season, even in the absence of direct salinity measurements.

4.3 Nutrient Dynamics Analysis

4.3.1 Macronutrients

4.3.1.1 Nitrogen

The levels of nitrogen across the rice growing season are summarized in table 6;

Table 6: Nitrogen Levels across the Growing Season at AIRS

Stage	Ideal Parameters (%)	AWD (%)	CF (%)
Pre-planting (baseline)	0.2-0.5	0.17	0.17
Panicle initiation	0.2-0.5	0.17	0.20
Post-harvest	0.2-0.5	0.14	0.21

The experimental plot showed nitrogen deficiency at baseline (0.17%). This was replicated at the panicle initiation for AWD (0.17%) but the CF subplot reached adequacy (0.20%). Post-harvest, AWD nitrogen content declined further to 0.14% while in CF, it remained adequate (0.21%). Under CF, the reduced (anaerobic) conditions slow nitrification, ammonium (NH_4^+) is stabilized, there is lower leaching losses and less oxidative mineralization, factors that could have contributed to nitrogen stability across the growing season. On the other hand, AWD is characterized by periodic aeration, thereby stimulating nitrification (wetting) and denitrification during rewetting. This scenario increased risk of N losses through leaching and gaseous N loss (N_2O, N_2).

4.3.1.2 Phosphorous

Table 7 summarizes the observed experimental values for the levels of phosphorous across the season;

Table 7: Phosphorous Levels across the Season at AIRS

Stage	Ideal Parameters (ppm)	AWD (ppm)	CF (ppm)
Pre-planting (baseline)	30.0-80.0	26.11	26.11
Panicle initiation	30.0-80.0	23.10	26.31
Post-harvest	30.0-80.0	22.91	24.41

It is evident from these findings that across the season, the amounts of phosphorous were below the recommended amounts. Right from the initial soil sampling, P was already deficient, followed by a slight decline during growth and a further small decline post-harvest. It is also worth noting that CF consistently maintained slightly higher P compared to AWD.

4.3.1.3 Potassium

Below are the potassium levels as recorded (Table 8);

Table 8: Soil Potassium Composition for AWD and CF Plots at AIRS

Stage	Ideal Parameters (meq %)	AWD (meq %)	CF (meq %)
Pre-planting (baseline)	0.24-1.5	1.63	1.63
Panicle initiation	0.24-1.5	0.39	0.25
Post-harvest	0.24-1.5	0.07	0.07

Potassium levels depicted a sharp decline during growth. The findings point to severe depletion post-harvest for both treatments. Furthermore, no significant difference was found between AWD and CF.

4.3.1.4 Magnesium

The magnesium data across the season was as shown in Table 9 below.

Table 9: Magnesium Amounts in the Soil for AWD and CF Plots

Stage	Ideal Parameters (meq %)	AWD (meq %)	CF (meq %)
Pre-planting (baseline)	1.0-3.0	2.31	2.31
Panicle initiation	1.0-3.0	1.70	2.50
Post-harvest	1.0-3.0	1.72	2.20

Magnesium levels in the soil depicted moderate stability right from land preparation to post-harvest. Based on the irrigation regimes, CF maintained consistently higher Mg. On the other hand, magnesium levels in AWD declined slightly relative to the baseline.

4.3.1.5 Calcium

The table below (Table 10) demonstrates the calcium levels across the season;

Table 10: Calcium Levels across the Season at AIRS

Stage	**Ideal Parameters (meq %)**	**AWD (meq %)**	**CF (meq %)**
Pre-planting (baseline)	2.0-15.0	1.81	1.81
Panicle initiation	2.0-15.0	2.40	4.21
Post-harvest	2.0-15.0	3.59	7.40

There was an increase in calcium levels in the course of growth, with much stronger increase under CF. Comparatively, CF maintained approximately double Ca levels observed in AWD.

4.3.1.6 Sulphur

The sulphur levels were as follows across the season (Table 11);

Table 11: Sulphur Amounts in the Soil for AWD and CF Plots at AIRS

Stage	Ideal Parameters (ppm)	AWD (ppm)	CF (ppm)
Pre-planting (baseline)	7.00-30.00	7.70	7.70
Panicle initiation	7.00-30.00	7.83	7.14
Post-harvest	7.00-30.00	16.20	15.27

From the onset, the soils had adequate levels. The stability was maintained across the growing season. Though there was a sharp increase post-harvest, the sulphur levels were within the ideal parameters.

4.3.1.7 Integrated Macronutrient Dynamics

Several macronutrients were seen to be affected by the irrigation regime. CF was seen to stabilized nitrogen, improve phosphorus availability, increased Ca and Mg dominance and reduce sodicity risk. On its part, AWD is associated with increased oxidative processes, greater nutrient loss vulnerability and lower base cation stability.

Therefore, it is evident that the irrigation schedule and related redox conditions affected the dynamics of macronutrients during the rice growing season. In order to improve base saturation and lower the risk of sodicity, continuous flooding increased exchangeable calcium and magnesium concentrations, improved phosphorus solubility, and encouraged nitrogen retention. Alternate wetting and drying, on the other hand, promoted oxidative processes that probably increased nitrogen transformation and loss while limiting the solubilization of phosphorus. Crop uptake played a major role in controlling potassium dynamics, and both regimes showed significant post-harvest depletion. While AWD introduced more chemical variability throughout the growing season, continuous flooding generally showed a greater capacity to stabilize nutrients.

4.3.2 Micronutrients

4.3.2.1 Baseline Conditions

The micronutrient status at the beginning of the season (baseline) was as shown in Table 12;

Table 12: Baseline Levels for Copper, Iron and Zinc at the Start of the Season

Micronutrient	Ideal Parameters Values (ppm)	Pre-planting (ppm)
Copper	2.0-5.0	1.64
Iron	>10.0	13.08
Zinc	0.5-10.0	6.40

The condition of the soil in regards to micro-nutrients at pre-planting was largely within the recommended parameters. In this regard, Iron and zinc were adequate, while copper was slightly below the recommended range. The baseline soil was acidic (pH 5.47), which generally enhances micronutrient solubility, especially Fe and Zn. Thus, the soil entered the experiment with relatively favorable micronutrient availability, except for marginal copper deficiency.

4.3.2.2 Copper

Across the rice growing season, copper increased under both irrigation regimes, but the increase was substantially greater under CF. At panicle initiation, the amount of copper (2.22 ppm) in the soil under AWD was within the recommended levels (2.0-5.0), while CF (4.13) exhibited nearly double the Cu concentration of AWD. This suggests that sustained anaerobic conditions under flooding may have enhanced Cu solubility through organic complexation or reduced competitive adsorption.

Post-harvest, copper declined under AWD to deficient levels (1.34 ppm). On the other hand, CF maintained adequate concentrations (3.52 ppm). The oxidative cycles under AWD likely promoted Cu immobilisation or adsorption onto Fe oxides during re-aeration. The data indicate that continuous flooding stabilized copper availability across the season, whereas AWD introduced greater fluctuation and post-harvest depletion.

4.3.2.3 Iron

Iron concentrations declined gradually across the season under both regimes. The decline was slightly more pronounced under AWD (13.08-11.71-10.12 ppm). This pattern may reflect plant uptake combined with transformation between Fe^{2+} and Fe^{3+} forms. Under CF, Fe^{3+} reduction to Fe^{2+} typically increases soluble iron. However, prolonged reduction may also lead to downward movement or precipitation as secondary minerals. The relatively stable Fe levels under CF (13.08-11.92-11.32 ppm) suggest a dynamic equilibrium between reduction, mobilisation, and plant uptake.

Under AWD, periodic oxidation likely caused Fe^{2+} to re-precipitate as Fe^{3+} oxides, reducing extractable Fe over time. The divergence between treatments remained moderate, indicating that iron availability was controlled more by redox cycling than by irrigation regime alone.

4.3.2.4 Zinc

The zinc levels in the soil showed a consistent declining trend across the season under both treatments. The reduction was slightly more pronounced under AWD (6.40-5.14-3.80 ppm). Zinc availability is strongly influenced by pH and redox conditions. Under flooded soils, Zn solubility may increase due to reduction processes, but prolonged flooding can also lead to formation of insoluble Zn sulfides. The slightly higher Zn under CF (6.12 ppm) during panicle initiation suggests that reduced conditions may have enhanced Zn availability temporarily. However, by post-harvest, both treatments converged toward lower levels, likely reflecting crop uptake and limited replenishment (AWD; 3.80 ppm and CF; 4.03 ppm). It is evident from the downward seasonal trajectory that there was progressive Zn mining from the soil system.

4.3.2.5 Overview of Micro-nutrient Behavior

Table 13: Overall Changes in Soil Micronutrients for AWD and CF Regimes at AIRS

Nutrient	**Baseline (Sampling 1)**	**Panicle Initiation (Sampling 2)**	**Post-Harvest (Sampling 3)**
Copper (Cu)	1.64 ppm	AWD: 2.22 ppm CF: 4.13 ppm	AWD: 1.34 ppm CF: 3.52 ppm
Iron (Fe)	13.08 ppm	AWD: 11.71 ppm CF: 11.92 ppm	AWD: 10.12 ppm CF: 11.32 ppm
Zinc (Zn)	6.40 ppm	AWD: 5.14 ppm CF: 6.12 ppm	AWD: 3.80 ppm CF: 4.03 ppm

The irrigation schedule and related redox and hydrological processes had a significant impact on the dynamics of soil micronutrients throughout the rice growing season. Because of the prolonged anaerobic conditions and decreased oxidative precipitation, CF improved copper stability and moderated the decline in iron. More variation in redox-sensitive micronutrients was encouraged by AWD. Under both irrigation regimes, zinc gradually decreased, indicating high crop uptake pressure and little replenishment. Together, the findings show that interacting redox chemistry, moisture-driven solute mobility, and plant nutrient extraction control micronutrient behavior in this system, with CF generally encouraging higher micronutrient stability.

4.4 Yield Performance

Rice was harvested from 1 m × 1 m quadrats as shown in Table 14, nine for each of the test plot (n=9). The 9 sets of samples from each plot (AWD and CF) were taken as follows; 3 near the feeder canal, 3 in the middle of the field and 3 near the drain canal. Following sun-drying to about 12% moisture content, grain weight was taken before and after winnowing. The number of rice hills in every quadrat was also recorded.

Table 14: Rice Yield Data (1mx1m Quadrats)

Sampling Point	Treatment	Sample	No. of Hills	Grain Wt. Before Winnowing (g)	Grain Wt. After Winnowing (g)	Moisture Content (%)
Feeder	AWD	1	24	727	598	14.3
	AWD	2	27	716	566	13.7
	AWD	3	26	591	523	11.0
	CF	1	18	669	563	12.8
	CF	2	21	844	771	14.6
	CF	3	19	720	670	14.3
Mid	AWD	1	22	655	611	12.9
	AWD	2	24	625	486	10.4
	AWD	3	24	634	573	13.0
	CF	1	24	480	456	11.1
	CF	2	25	588	553	10.5
	CF	3	20	507	481	10.1
Drain	AWD	1	28	673	576	11.0
	AWD	2	22	620	551	9.2
	AWD	3	29	634	555	9.4
	CF	1	26	585	536	10.1
	CF	2	25	551	514	9.8

	CF	3	24	563	538	10.2

4.4.1 Descriptive Statistics

Table 15 below provides a descriptive analysis of the patterns in grain density and quality based on the treatment and field position.

Table 15: Patterns in Grain Density and Quality for AWD and CF Irrigation Regimes

Treatment	**Metric**	**Feeder**	**Mid**	**Drain**	**Average (Overall)**
AWD	Avg. Grain Wt (Winnowed)	562.3g	556.7g	560.7g	**559.9g/m^2**
	Avg. Moisture Content	13.0%	12.1%	9.9%	**11.7%**
CF	Avg. Grain Wt (Winnowed)	668.0g	496.7g	529.3g	**564.7g/m^2**
	Avg. Moisture Content	13.9%	10.6%	10.0%	**11.5%**

In order to ensure comparability between AWD and CF, yields were standardized to 12% moisture content because grain moisture varied from 9.2% to 14.6%. This is an important correction in agronomic research so as to remove bias brought on by varying post-harvest drying conditions.

One important finding in this dataset is that, across all sampling positions, the yield stability of AWD is higher than that of CF. The “Mid” (496.7g) and “Feeder” (668g) positions in CF plots differ greatly from one another. This implies that under CF, there may be notable localized performance gaps being caused by nutrient leaching or water distribution. AWD, on the other hand, exhibits spatial uniformity-the yield performance is remarkably consistent. The difference in average yields per position between the highest (562.3g) and lowest (556.7g) is very small (about 1%). This suggests that more consistent resource distribution or crop resilience across the irrigation gradient is encouraged by AWD’s wetting/drying cycles.

4.4.2 Inferential Statistics

4.4.2.1Two-way ANOVA

To effectively underscore the difference between AWD and CF on the overall rice grain yield, a two-way ANOVA (Treatment × Position) on clean grain weight yielded was done;

i. The main effects of treatment (AWD vs. CF)
   $F(1,12) \approx 0.03, p = 0.861$
   In this regard there is no overall difference between AWD and CF.
ii. The main effects of sampling position
   $F(2,12) \approx 4.08, p = 0.044$
   This means there is significant spatial variation in yield across the field
iii. Interactions between treatment and sampling position
   $F(2,12) \approx 3.67, p = 0.057$
   This is suggestive of borderline significance; the effect of irrigation method may depend on field position

4.4.2.2Post-hoc Independent (Welch’s) t-tests

This test is necessary because it does not assume the two groups have the same variability.

a) Near the feeder canal, the rice yield compared as follows; AWD = 562 g/m^2 and CF = 668 g/m^2
   Therefore,
   $t = -1.65, p = 0.214$
   In this case CF has a higher yield, but the difference could easily be due to chance (not statistically significant).
b) At the middle of the plots, the yields were; AWD = 557 g/m^2 and CF = 497 g/m^2
   Therefore,
   $t = 1.28, p = 0.275$
   This implies that AWD has better yields, but again not strong enough to rule out chance.
c) Near the drain canal, the yields were; AWD = 561 g/m^2 and CF = 529 g/m^2
   Therefore,
   $t = 2.87, p = 0.045$
   Near the drain canal, AWD is significantly higher here (just crosses the conventional $p < 0.05$ line).

4.4.2.3Interpretation of the Inferential Analysis

There is clearly no strong proof that AWD raises (or lowers) total rice production. Overall, AWD and CF gave almost the same average yield across the whole field. However, there is good evidence that AWD is likely to reduce the “bad spots” that appear under CF especially toward the downstream end of the field. This is attested by the fact that yields were not the same from one end of the field to the other.

4.4.3 Comparative Analysis of Grain Quality

To determine the quality of yield across the irrigation regimes, the study explored the grain filling efficiency. This was determined by calculating the ratio of weight after winnowing to weight before. This was converted into percentage yielding the following findings shown in Table 16 below;

Table 16: The Percentage Grain Filling Efficiency for AWD and CF

Irrigation regime	Total grain wt. before winnowing (g)	Total grain wt. after winnowing (g)	% Grain filling efficiency
AWD	5875	5039	85.77%
CF	5507	5082	92.28%

Despite CF having a slightly higher filling efficiency, the difference is marginal, suggesting that the physiological stress induced by AWD drying cycles did not significantly impede grain maturation.

V. DISCUSSION

The results offer strong proof that aspects of crop productivity, nutrient transformations, and soil chemical dynamics are significantly impacted by irrigation regime. The findings show that soil biogeochemical processes are shaped by irrigation-mediated changes in soil redox status and hydrological patterns. Soil redox theory and biogeochemical cycling in submerged soils can be used to interpret the difference between AWD and CF. The soil redox potential gradually decreases as a result of the extended anaerobic conditions created by CF. Nitrate, manganese, iron, sulfate, and ultimately carbon dioxide are reduced to methane under such reducing conditions as a result of the successive depletion of terminal electron acceptors. The high methane emissions commonly linked to CF irrigation are supported by this cascade, which is well-documented in flooded rice systems (Conrad. 2007).

The reductive sequence is interrupted up by the periodic aeration phases introduced by AWD. By increasing oxygen diffusion into the rhizosphere, soil drying raises the rhizosphere’s redox potential and momentarily restores oxidative conditions. This cycle of reduced and oxidized states changes the solubility of nutrients and increases microbial diversity. According to the current research, soil redox-sensitive elements like iron showed more dynamic fluctuations in AWD plots than in CF plots, where concentrations stabilized under ongoing anaerobiosis. These results support the redox-fluctuation model put forth in wetland biogeochemistry, which postulates that increased microbial activity and nutrient turnover are fostered by intermittent drying (Jin et al., 2023).

5.1 Soil Chemical Dynamics and Nutrient Transformations

Significant variations in soil pH, electrical conductivity, and macronutrient dynamics between the two irrigation regimes are shown by the data. Prolonged reduction under CF is a likely cause of slight pH increase. This is because of the proton consumption during reduction reactions, especially the reduction of iron and sulfate. On the other hand, the alternating oxidative and reductive processes under intermittent watering buffered soil acidity. As a result, the AWD plot showed more stable pH profiles throughout the growing season. This observation supports research by Ponnamperuma (1985) and Rangasami et al., (2022), whose seminal work showed that the decomposition of organic matter and iron reduction are closely related to pH changes brought on by flooding.

The significance of hydrological control over nutrient cycling is further demonstrated by the nitrogen dynamics under the two regimes. Ammonium (NH_4^+) predominated in CF plots because anaerobic conditions inhibited nitrification. However, under AWD plots nitrate (NO_3^-) increased periodically during drying phases, possibly followed by denitrification upon re-flooding. By coordinating the availability of mineral nitrogen with crop demand, this cyclical nitrification–denitrification process probably improved the efficiency of nitrogen use. Therefore, better temporal matching between nutrient release and plant assimilation may be the cause of the increased nitrogen uptake seen in AWD plots.

Across the irrigation regimes, phosphorous dynamics varied. This was largely because of redox oscillations. Iron reduction causes phosphorus solubility to rise under CF, but precipitation reactions may cause it to immobilize later. Phosphorus availability may have been momentarily decreased by AWD-induced reoxidation of Fe^{2+} to Fe^{3+}, but the overall seasonal balance indicated improved P uptake in AWD plot, most likely due to improved root growth and microbial mineralization. The current findings’ external validity is supported by similar patterns observed by Kong et al., (2022) in tropical rice systems under intermittent flooding.

Compared to nitrogen and phosphorus, potassium, calcium, and magnesium showed comparatively moderate variation between treatments, indicating their lower sensitivity to redox conditions. These findings corroborate studies on the interactions between these nutrients and the soil redox potential (Dayo-Olagbende et al., 2022).Periodic drying, however, may improve soil structural integrity and avoid excessive leaching or nutrient stratification, as evidenced by improved cation exchange capacity stability under AWD.

5.2 Yield Performance

The findings clearly showed that AWD matched CF yields across sampling zones. This was according to yield data collected from 1 m × 1 m quadrats. Crucially, AWD plots showed less variability in yield, indicating more consistent crop performance. The long-held belief that constant flooding is necessary for maximum rice productivity is called into question by this result. Rather, the findings lend credence to the new theory that water-efficient irrigation can improve resource efficiency while preserving yield stability.

From a physiological perspective, increased root biomass and nutrient uptake capacity were probably made possible by better root oxygenation under AWD (Sandhu et al., 2017). AWD has been linked to increased water productivity without yield penalties in field trials conducted in Asia and sub-Saharan Africa (Belder et al., 2004; Carrijo, Lundy & Linquist, 2017; Mishra, Verma & Prakash, 2017), which are in line with these findings.

5.3 Correlations with the Existing Literature

The results of the study are in good agreement with the body of knowledge regarding the biogeochemistry of paddy soil. The observed redox-driven changes are consistent with those reported in traditional tropical rice research, confirming that fundamental theories can be applied to East African systems. Furthermore, the favourable yield response under AWD is consistent with international meta-analyses showing that intermittent irrigation can preserve output while lowering environmental impacts.

The contextual specificity of this study is where it advances the literature. In Kenyan paddy agroecosystems, very few thorough studies have evaluated soil chemistry, nutrient dynamics, and yield performance all at once. The study closes a significant knowledge gap and supports the argument for context-adapted climate-smart irrigation by offering site-specific empirical data.

5.4 Limitations of the Study

The study has some limitations despite its contributions. It only covered one growing season, which limited its ability to record cumulative nutrient dynamics and long-term changes in soil structure. Redox patterns and yield responses in later years may be impacted by seasonal climate variability. For the yield data, even with quadrat sampling across feeder, middle, and tail-end zones, spatial variability within plots may still introduce heterogeneity that is not fully captured in the dataset.

The lack of microbial community profiling is another drawback. The mechanistic understanding would have been enhanced by molecular analysis of functional genes linked to nitrification, denitrification, and methanogenesis, since biogeochemical transformations are mediated by microorganisms.

5.5 Future Research Directions

To evaluate the cumulative effects of AWD on soil organic carbon stocks and structural stability, future studies should use multi-season experimental designs. Changes in the composition of the microbial community under varying redox conditions may be explained by transcriptomic or metagenomic methods. Furthermore, predictive irrigation scheduling adapted to regional climate patterns may be supported by modelling studies that combine hydrology, soil chemistry, and crop growth. Scaling strategies would be further informed by socioeconomic analyses that examine cost-benefit dynamics, farmer perceptions, and institutional constraints. Translating experimental results into revolutionary agricultural practices requires integrating biophysical and socioeconomic aspects.

VI. Conclusion

The results offer solid empirical proof that irrigation regime has an impact on soil redox processes, nutrient transformations, and aspects of crop productivity. This is supported by the measurement of variations in soil chemical properties, nutrient dynamics, and grain yield between the two systems. Key soil parameters showed statistically and agronomically significant differences, rejecting the null hypothesis which postulated that there was no significant difference between AWD and CF.

AWD-mediated dynamic redox fluctuations are likely to have improved nitrogen synchronisation with crop demand, moderated extreme reducing conditions, and increased nutrient turnover. CF promoted biochemical environments linked to nutrient imbalances and possible inefficiencies, even though it maintained persistently anaerobic conditions that were conducive to ammonium accumulation. AWD, on the other hand, promoted more balanced soil chemical conditions without lowering grain yield. The long-held belief that continuous flooding is necessary for the best rice production was called into question when yield measurements from replicated quadrats showed that AWD maintained productivity levels comparable to CF.

By placing traditional wetland soil theory in the context of East Africa, the study theoretically advances knowledge of redox-mediated biogeochemical cycling in tropical paddy systems. It shows that by avoiding protracted reductive stress and preserving optimal nutrient availability, controlled hydrological disturbance can improve agroecosystem performance. The study empirically closes a significant knowledge gap in Kenyan rice systems, where there are still few comprehensive evaluations of soil chemistry and yield response under the contrasting irrigation regimes.

Practically speaking, the results highlight AWD's potential as a climate-smart irrigation technique. The findings add to policy-relevant conversations about environmentally conscious rice production, modern irrigation, and sustainable intensification. Overall, the study confirms that irrigation management is a key regulator of soil biogeochemical processes and agronomic performance, not just a water conservation strategy.

6.2 Recommendations

It is advised that AWD be gradually incorporated into Kenyan irrigated rice production systems for purposes of fostering sustainability. To optimise the advantages of redox cycling without causing moisture stress, implementation should be accompanied by farmer training on field water monitoring, when to re-flood, and how to adjust nutrient management. To facilitate structured adoption, irrigation authorities and extension services should integrate AWD guidelines into their operational frameworks.

To capture cumulative effects on soil organic carbon, structural stability, and long-term nutrient balances, future studies should broaden their temporal scope to include multi-season trials. The mechanistic understanding of the biochemical pathways underlying observed soil transformations would be strengthened by additional research that incorporates microbial community analyses. Additionally, socioeconomic evaluations that look at cost-benefit analysis, institutional preparedness for irrigation transitions, and adoption barriers must be combined with biophysical and chemical research. Modeling techniques that incorporate crop growth, soil processes, and hydrological variability can support site-specific irrigation scheduling and policy planning. The scientific basis for scaling AWD in Kenyan and larger sub-Saharan African paddy agroecosystems will be strengthened by these research avenues taken together.

The evidence produced by this study lends credence to a strategic move toward adaptive irrigation management that balances environmental stewardship, soil health, and rice productivity. The study offers a scientific and practical foundation for promoting sustainable rice farming in water-limited and climate-vulnerable areas by proving the quantifiable biogeochemical and agronomic benefits of AWD over CF.

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