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Mitigating Iron Toxicity and Enhancing Rice Growth Through Periodic Flooding in Tropical Ultisol Fields with Low Productivity

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ABSTRACT

Iron toxicity is a major constraint in rice cultivation on tropical Ultisol soils, particularly in fields with a history of low productivity. Continuous flooding in paddy systems exacerbates this issue by increasing Fe^{2+} availability, leading to toxicity at high concentrations. This study evaluated periodic flooding and drying as a sustainable water management strategy to mitigate Fe^{2+} toxicity and enhance rice growth. A greenhouse experiment was conducted using a completely randomized design with five treatments and five replications, assessing different flooding and drying intervals. Soil pH and Fe^{2+} concentrations were measured at the end of the experiment, along with key rice growth and yield parameters. Results showed that extended drying intervals significantly improved soil pH and reduced Fe^{2+} concentrations, mitigating toxicity. The treatment with three weeks of drying followed by three weeks of flooding resulted in the lowest Fe^{2+} concentration (4.08 ppm) and the most stable pH conditions. However, the highest rice productivity was observed in the two-week flooding–two-week drying treatment, which promoted increased plant height, tiller number, and grain yield. These findings highlight the potential of periodic flooding as a practical and sustainable approach to improve soil health and rice productivity in iron-toxic Ultisol fields. This study contributes to developing effective water management strategies for rice cultivation in

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marginal tropical soils, addressing both environmental sustainability and agricultural productivity. Future research should explore the long-term impacts of periodic flooding on soil nutrient dynamics and its applicability across diverse tropical agroecosystems

Keywords: Periodic flooding, soil iron management, ultisol paddy fields, sustainable water practices, tropical soil health

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INTRODUCTION

Rice (*Oryza sativa L.*) is a staple crop for over half of the global population, particularly in tropical regions, where it serves as a critical source of calories and livelihood for millions of smallholder farmers (Purnama et al., 2023a). However, rice cultivation in marginal tropical soils, such as Ultisols, faces numerous challenges due to inherent soil limitations (Saleem et al., 2023). Ultisols, which dominate large areas in Southeast Asia, including Indonesia, are characterized by their acidic nature, low nutrient availability, and high concentrations of exchangeable aluminium and iron (Mureithi et al., 2024; Soelaeman & Haryati, 2012). These conditions severely constrain crop productivity, necessitating innovative soil and water management strategies to unlock the agricultural potential of such soils.

Iron (Fe) toxicity is a particularly significant constraint in rice cultivation on Ultisols, especially under continuous flooding conditions. Waterlogged soils promote the reduction of Fe^{3+} to Fe^{2+}, a highly soluble and toxic form of iron that interferes with root development, nutrient uptake, and photosynthesis (Aung & Masuda, 2020; Leinonen, 2023; Ponnamperuma, 1972; Wairich et al., 2024). Over time, high Fe^{2+} concentrations can lead to severe yield losses, as observed in many newly opened Ultisol fields where farmers struggle with persistently low productivity despite the use of organic and synthetic fertilizers (Andrew et al., 2020; Purnama et al., 2023b). These soils often exhibit unstable chemical properties, with highly acidic pH levels and poor nutrient cycling, further exacerbating the challenges of rice cultivation.

Although previous studies have demonstrated the potential of periodic flooding and drying (intermittent irrigation) to mitigate Fe toxicity by promoting soil redox dynamics, much of this research has been conducted in established rice systems with relatively stable soil properties (Andrew et al., 2020; Dossou-Yovo et al., 2023; Saidi et al., 2021). For example, Andrew et al. (2020) and Dossou-Yovo et al. (2023) showed that alternating wet and dry conditions reduce Fe^{2+} concentrations and stabilize soil pH, thereby minimizing iron toxicity and supporting rice productivity. However, in established paddy fields, long-term cultivation fosters the accumulation of soil organic matter and the development of adapted microbial communities, which actively regulate Fe^{2+} solubility and buffer redox fluctuations (Kögel-Knabner et al., 2010; Ninin et al., 2024; Tan et al., 2019). The presence of Fe–organic matter complexes and a well-developed microbial iron-reducing community helps stabilize Fe^{2+} levels under flooded conditions while preventing excessive oxidation when drained, making the response to intermittent irrigation more predictable (Pett-Ridge & Firestone, 2005; Wu et al., 2019). These studies primarily focus on systems with mature nutrient cycling and consistent management practices, whereas newly opened Ultisols exhibit more pronounced fluctuations in redox potential due to their undeveloped biological and chemical equilibria.

Newly opened Ultisol fields, by contrast, are characterized by high acidity ($pH < 5$), unstable redox conditions, and excessive soluble Fe^{2+} concentrations, which are not yet fully equilibrated due to the lack of long-term cultivation. Unlike in well-established paddy soils, where Fe^{2+} accumulation is moderated by organic matter interactions and microbial Fe reduction-oxidation cycles, newly opened Ultisols lack these buffering mechanisms, leading to rapid and unpredictable changes in Fe^{2+} solubility (Pett-Ridge & Firestone, 2005; Wu et al., 2019). Studies have shown that tropical soils recently converted to paddy systems experience erratic Fe^{2+} mobilization due to sharp redox fluctuations, which only stabilize after several years of cultivation (Wu et al., 2019). Similarly, in newly cultivated Ultisols, the absence of well-established microbial and chemical equilibria leads to higher variability in Fe^{2+} solubility compared to older paddies, where organic matter accumulation and iron oxide transformations help buffer redox cycles (Ninin et al., 2024).

While the effectiveness of periodic flooding has been established in traditional paddy systems, its impact on Fe dynamics, pH stabilization, and rice productivity in newly opened Ultisol fields remains underexplored. The extreme conditions in Ultisols, including rapid changes in redox potential and nutrient availability, pose challenges for extrapolating findings from established systems to these marginal tropical soils. This difference raises questions about whether the same periodic flooding strategies used in mature paddy fields will yield similar benefits in newly cultivated Ultisols, where chemical instability could either amplify or diminish the expected effects. This gap in understanding hinders the development of water management strategies tailored to newly cultivated Ultisols.

This study addresses the critical knowledge gap by examining the effects of periodic flooding on Fe concentrations in floodwater, soil pH, and rice growth and productivity in newly opened Ultisol fields. Unlike previous research, which often emphasizes broader soil health metrics and microbial activity (Freitas et al., 2024; Majumdar et al., 2023), this study focuses specifically on how varying flooding and drying intervals influence Fe^{2+} solubility, pH fluctuations, and observable plant responses such as growth and yield. Given the extreme redox variability and chemical instability in newly cultivated Ultisols, understanding how periodic flooding modulates Fe^{2+} dynamics in these soils is crucial for developing effective water management strategies. By targeting these specific parameters, the study provides actionable insights into mitigating Fe toxicity and improving rice productivity in newly cultivated Ultisols. These findings hold broader significance for enhancing food security in tropical regions where rice is a staple crop and where iron toxicity limits yields. Furthermore, optimizing periodic flooding as a water management strategy not only improves crop resilience but also promotes efficient water use, reducing the need for continuous submergence and mitigating risks associated with water scarcity and climate variability in rice-growing areas.

MATERIALS AND METHODS

Study Site and Soil Collection

The study was conducted in a greenhouse at Universitas Lancang Kuning, Riau, Indonesia. Ultisol soil was collected from paddy fields in Muara Kelantan Village, Siak Regency, Riau, Indonesia (0.577° N, 101.424° E). The fields have been cultivated for five years, utilizing both organic and synthetic fertilizers. Despite these efforts, persistent low productivity and symptoms of iron toxicity were observed. Soil samples were taken from the top 0–20 cm layer using a composite sampling method to represent the overall field characteristics. The collected soil was air-dried, sieved to 2 mm, and analysed for initial properties, including pH, organic carbon, nitrogen, phosphorus, and exchangeable iron (Fe). Soil analysis followed standard protocols as outlined by Association of Official Analytical Chemists (1995).

Experimental Design

The experiment was designed as a completely randomized design (CRD) with five treatments and five replications, resulting in a total of 25 experimental units. Each unit consisted of a polybag filled with 10 kg of air-dried Ultisol soil. The treatments evaluated different flooding and drying intervals to assess their effects on Fe dynamics, soil pH, and rice (*Oryza sativa* L.) productivity.

The treatments included continuous flooding throughout the experiment (A0), alternating 2 weeks of flooding followed by 2 weeks of drying (A1), alternating 2 weeks of drying followed by 2 weeks of flooding (A2), alternating 3 weeks of flooding followed by 3 weeks of drying (A3), and alternating 3 weeks of drying followed by 3 weeks of flooding (A4). Water management across treatments followed distinct flooding and drying cycles. During the flooding phases, water levels were maintained at 5 cm above the soil surface, as depicted in the schematic

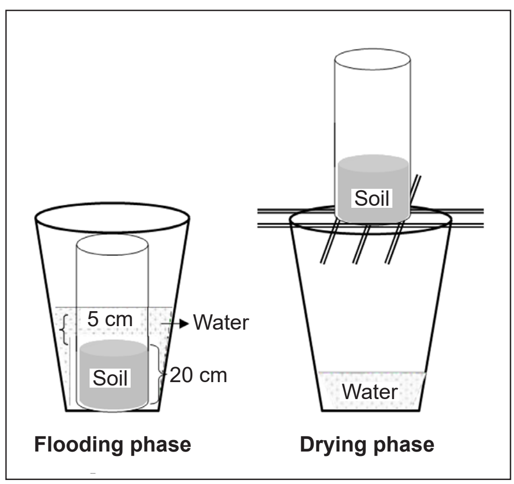

Figure 1. Schematic representation of the experimental flooding and drying treatments

diagram (Figure 1). During the drying phases, polybags were elevated to allow complete drainage, mimicking natural drying conditions in the field. The transition between flooding and drying was carefully controlled to ensure accurate simulation of alternating anaerobic and aerobic soil conditions.

Rice Cultivation

The rice variety *Inpari 42* was selected due to its adaptability to lowland conditions and moderate tolerance to Fe toxicity. Seeds were pre-germinated by soaking in water for 48 hours before being sown directly into the polybags. Three seedlings were transplanted into each polybag, and standard agronomic practices were followed. Fertilizers were applied in three stages: basal application at planting, during the tillering stage, and at panicle initiation. Urea was applied at 50 kg/ha, SP-36 at 75 kg/ha, and KCl at 50 kg/ha to meet the nitrogen, phosphorus, and potassium requirements of the crop. Pest and disease management was carried out as required, using environmentally friendly pesticides to ensure crop health (Purnama et al., 2025, 2024).

Data Collection and Measurements

Data collection focused on soil chemical parameters and plant growth and productivity. Soil pH was measured to evaluate the effects of periodic flooding and drying on the chemical properties of Ultisol soil. Measurements were conducted at specific intervals during the experiment to capture changes in pH associated with different water management regimes. A calibrated digital pH meter (Hanna Instruments, HI 98191) was used, following a 1:2 soil-to-water ratio protocol.

For the continuous flooding treatment (A0), pH was measured weekly to monitor soil acidity stability under anaerobic conditions. For periodic flooding and drying treatments (A1, A2, A3, A4), pH measurements were taken at the end of each flooding phase to capture the cumulative effect of prolonged reducing conditions on Fe^{2+} solubility. This timing was selected because Fe^{2+} progressively accumulates under anaerobic conditions and typically reaches peak concentrations at the end of the flooding cycle, making this phase the most critical for evaluating iron toxicity risks. While monitoring pH across both flooding and drying phases could provide additional insights into dynamic redox fluctuations, logistical constraints—such as field accessibility and sample preservation—limited the feasibility of continuous measurement. Thus, pH was recorded during the phase where Fe^{2+} levels were expected to be most representative of reducing conditions. Soil samples were collected from each polybag at a depth of 5–10 cm to ensure consistency across treatments. Each sample was thoroughly mixed before preparing a 1:2 soil-to-water suspension, which was stirred and allowed to settle for 30 minutes prior to pH measurement. All measurements were replicated three times per sample to ensure accuracy.

Fe^{2+} concentrations in the soil solution were analysed at the end of the study period, specifically after the final flooding phase for each treatment, using an Atomic Absorption Spectrophotometer (PerkinElmer AAnalyst 800), following the method described by Mahender et al. (2019). This approach was chosen to capture the cumulative effect of periodic flooding and drying cycles on Fe^{2+} solubility, providing a representative measurement of iron availability under the prevailing redox conditions at the conclusion of the experiment. Plant growth was assessed by measuring plant height and the number of tillers per plant at weekly intervals throughout the growth cycle. At harvest, yield components were recorded, including the number of panicles per plant, the percentage of filled grains, 100-grain weight, and dry grain weight per polybag, after drying to 12% moisture content.

Statistical Analysis

The collected data were analysed using Analysis of Variance (ANOVA) to evaluate the effects of treatments on soil and plant parameters. Duncan's Multiple Range Test (DMRT) was applied to compare treatment means when significant differences ($p < 0.05$) were identified. Statistical analyses were performed using SPSS software (version 25.0).

RESULTS AND DISCUSSION

Initial Soil Characteristics

The initial analysis of the soil from newly opened paddy fields in Muara Kelantan Village, Siak Regency, Indonesia revealed key chemical properties that characterize the challenges of cultivating rice in marginal Ultisol soils. Table 1 summarizes the key chemical properties of the soil, emphasizing the balance between nutrient potential and challenges for sustainable rice cultivation.

The chemical analysis showed that the soil exhibited a highly acidic pH of 4.70, which significantly limits nutrient availability and promotes the solubility of toxic elements such as aluminium (Al) and iron (Fe). Acidic soils are a common characteristic of Ultisols, particularly in tropical regions, and often require careful management to improve their suitability for agricultural purposes (Swe & Funakawa. 2023). Organic carbon content was very high at 14.3%, reflecting significant accumulation from previous organic matter applications. Despite this, the total nitrogen content was moderate at 0.43%, resulting in a very high carbon-to-nitrogen (C/N) ratio of 33.3. This imbalance suggests slow organic matter decomposition and limited nitrogen availability for plant uptake, which can constrain microbial activity and nutrient cycling in the soil (Kuśmierz et al., 2023; Li et al., 2022).

Phosphorus availability was exceptionally high at 107.4 ppm, likely due to prior synthetic fertilizer applications. While this is beneficial, acidic soil conditions may still

Table 1
Initial soil chemical properties of paddy fields in Muara Kelantan

No	Analysis	Value	Category
1	pH H_2O	4.70	Acidic
2	Organic carbon (%)	14.3	Very high
3	Total nitrogen (%)	0.43	Moderate
4	C/N ratio	33.3	Very high
5	Available phosphorus (ppm)	107.4	Very high
6	Exchangeable bases		
	a. Ca (cmol(+)/kg)	8.18	Moderate
	b. Mg (cmol(+)/kg)	4.37	High
	c. K (cmol(+)/kg)	0.89	High
	d. Na (cmol(+)/kg)	0.13	Low
7	Cation exchange capacity (CEC) (cmol(+)/kg)	32.2	High
8	Exchangeable aluminium (Al) (cmol(+)/kg)	7.17	Moderate
9	Aluminum saturation (%)	22.27	Low
10	Base saturation (%)	42.1	High
11	Exchangeable iron (Fe) (ppm)	4881	Very high

lead to phosphorus fixation, reducing its bioavailability over time (McDowell et al., 2024). Among the exchangeable base cations, calcium (Ca) was moderate at 8.18 cmol(+)/kg, magnesium (Mg) and potassium (K) were high at 4.37 and 0.89 cmol(+)/kg, respectively, and sodium (Na) was low at 0.13 cmol(+)/kg. These values reflect adequate nutrient reserves for crop growth, although the low sodium levels indicate minimal salinity, which is favourable for rice cultivation (Fujii et al., 2018). The cation exchange capacity (CEC) was high at 32.2 cmol(+)/kg, showing the soil's potential to retain and supply nutrients effectively, despite its acidic nature.

Despite these favourable characteristics, the exchangeable aluminium concentration was 7.17 cmol(+)/kg, which poses a moderate risk of aluminium toxicity, especially at low pH. However, the aluminium saturation was relatively low at 22.27%, reducing its immediate impact on plant health (Saidi et al., 2021). Base saturation was high at 42.1%, suggesting that a significant proportion of exchange sites were occupied by beneficial cations like Ca, Mg, and K, providing partial buffering against acidity.

The most critical constraint identified was the extremely high concentration of exchangeable iron at 4881 ppm, which presents a severe risk of iron toxicity under waterlogged conditions. Such high Fe levels are typical in acidic soils subjected to flooding, where reducing conditions increase Fe solubility (Aung & Masuda, 2020; Wairich et al., 2024). Iron toxicity can severely impact rice growth by interfering with root development, nutrient uptake, and overall plant performance. These findings align with earlier studies, highlighting that while Ultisol soils may have high nutrient reserves due to prior management efforts, they remain constrained by acidity and toxic iron levels, requiring targeted management strategies to improve productivity (Noor et al., 2012).

Effects of Periodic Flooding on Soil pH

Soil pH plays a vital role in determining nutrient availability, microbial activity, and the solubility of toxic elements such as aluminium (Al) and iron (Fe). In this study, soil pH was measured at the end of the flooding phases for each treatment to assess the cumulative impact of periodic flooding on the chemical properties of Ultisol soils. The results, presented in Table 2, illustrate how different flooding and drying regimes influenced soil pH dynamics.

For continuous flooding (A0), pH remained relatively stable throughout the experiment, with values ranging from 6.27 to 7.44. This stability reflects the dominance of reducing conditions under constant submergence, which tends to increase pH by promoting the reduction of Fe^{3+} to Fe^{2+} and the accumulation of bicarbonates and other reduced compounds (Amini et al., 2022; Ponnamperuma, 1972). These conditions are characteristic of continuously flooded soils but can also lead to excessive solubility of Fe^{2+}, posing risks of iron toxicity.

In treatments involving periodic flooding and drying (A1 to A4), soil pH varied depending on the timing and duration of the flooding phases. In A1 (2 weeks flooding, 2 weeks drying), pH dropped during shorter flooding periods, reaching a low of 5.68 in week 6. The relatively acidic conditions can be attributed to the incomplete reduction of acidic compounds during the brief flooding intervals and the carryover effects of acidification from the preceding drying phases (Wang et al., 2022). In A2 (2 weeks drying, 2 weeks

Table 2
*Average soil pH under periodic flooding in Ultisol fields cultivated with rice (*Oryza sativa *L.) (n = 5)*

Week	A0	A1	A2	A3	A4
2	6.67	6.33	-	-	-
3	6.73	-	-	6.74	-
4	6.54	-	6.49	-	-
5	6.35	-	-	-	-
6	6.27	5.68	-	-	5.53
7	6.61	-	-	-	-
8	6.62	-	6.14	-	-
9	6.62	-	-	6.37	-
10	6.60	6.43	-	-	-
11	6.66	-	-	-	-
12	6.70	-	7.18	-	6.26
13	7.40	-	-	-	-

Note. Data = means

flooding), the pH increased significantly during the flooding phases, reaching 7.18 in week 12. The drying phases preceding each flooding period likely enhanced the oxidation of Fe^{2+} to Fe^{3+}, reducing the availability of soluble Fe^{2+} and consequently lowering soil acidity (Leinonen, 2023). This treatment demonstrated the most effective stabilization of soil pH among the shorter flooding-drying cycles.

The treatment with 3 weeks flooding followed by 3 weeks drying (A3) exhibited consistently stable pH levels, ranging from 6.37 to 6.74. The longer flooding intervals allowed for more complete reduction of acidic components, while the subsequent drying phases minimized the accumulation of toxic ions by promoting oxidation and precipitation of $Fe(OH)_3$ and $Al(OH)_3$. Similarly, A4 (3 weeks drying followed by 3 weeks flooding) showed pH dynamics reflecting the extended oxidation effects of longer drying phases, with the lowest observed pH of 5.53 in week 6. However, pH gradually increased during the flooding phases, indicating the ameliorative effects of periodic submergence.

Periodic flooding modulated soil pH by alternating between reducing and oxidizing conditions. During flooding phases, Fe^{3+} was reduced to Fe^{2+}, leading to a temporary decrease in acidity and an accumulation of basic compounds, while drying phases facilitated Fe^{2+} oxidation and the precipitation of insoluble hydroxides (Kögel-Knabner et al., 2010; Ninin et al., 2024). This dynamic cycle contributed to pH stabilization in Ultisols, with treatments like A2 and A3 showing the greatest potential for improving soil conditions for rice cultivation (Saidi et al., 2021). However, as pH was measured only at the end of the flooding phase, this study primarily captured the cumulative effects of prolonged reduction but did not fully account for fluctuations during the drying phase. Since redox conditions continue to evolve throughout both phases, future research should incorporate real-time pH monitoring across the entire flooding-drying cycle to better understand short-term variations in Fe solubility and their implications for long-term soil chemistry (Wu et al., 2019). Despite this limitation, these findings suggest that periodic flooding and drying can serve as a promising strategy for stabilizing soil pH and mitigating Fe toxicity in newly cultivated Ultisols, contributing to more sustainable rice production on marginal soils.

Effects of Periodic Flooding on Fe Dynamics

Periodic flooding significantly alters iron (Fe) dynamics in Ultisol soils, which are commonly characterized by high levels of exchangeable Fe and acidic conditions. In this study, Fe^{2+} concentrations and soil pH were assessed under different flooding and drying regimes to evaluate their effects on mitigating iron toxicity, a critical challenge in rice cultivation on these marginal soils. Figure 2 illustrates the effects of periodic flooding on Fe concentrations in floodwater under different treatments.

Continuous flooding (A0) maintained Fe^{2+} concentrations at an estimated average of 7.49 ppm, indicating stable but strongly reducing conditions that favoured the accumulation

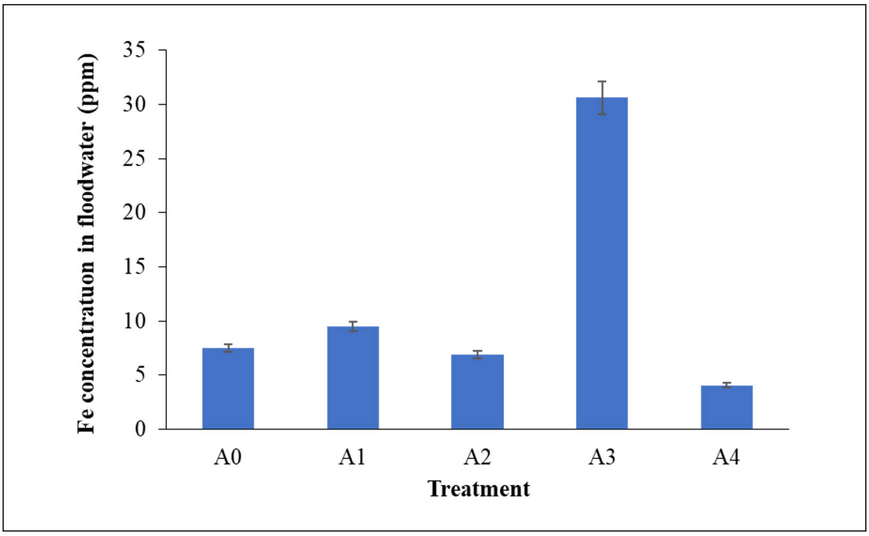

Figure 2. Effects of periodic flooding on Fe dynamics (*n* = *5*)

of soluble Fe^{2+}. This concentration was higher than in periodically drained treatments, suggesting sustained Fe^{3+} reduction without intermittent oxidation. The relatively stable pH range of 6.27 to 7.44 reflects bicarbonate formation and continuous Fe^{3+} reduction under anaerobic conditions (Amini et al., 2022). Although periodic drying phases in other treatments led to Fe^{2+} reoxidation, the absence of such fluctuations in A0 resulted in prolonged Fe^{2+} availability. This persistent presence of soluble Fe^{2+} under continuous flooding poses risks of chronic iron toxicity, as rice roots remain exposed to excessive iron concentrations for an extended duration (Aung & Masuda, 2020; Wairich et al., 2024).

Periodic flooding with shorter drying intervals, such as in treatment A1 (2 weeks flooding followed by 2 weeks drying), resulted in an Fe^{2+} concentration of 9.49 ppm by the end of the experiment. This increase can be attributed to incomplete oxidation of Fe^{2+} during the brief drying phases, which limited the conversion of soluble Fe^{2+} into insoluble Fe^{3+}. The pH in A1 also dropped as low as 5.68, further increasing Fe solubility under acidic conditions (Saleem et al., 2023). These findings suggest that shorter drying intervals may be insufficient to effectively mitigate iron toxicity in soils with high Fe levels.

In contrast, treatment A2, which involved 2 weeks of drying followed by 2 weeks of flooding, led to a more controlled Fe^{2+} concentration of 6.92 ppm. The longer drying intervals allowed for enhanced oxidation of Fe^{2+}, reducing its solubility and toxicity during subsequent flooding phases. This treatment also stabilized soil pH, which peaked at 7.18 during flooding, suggesting that alternating aeration and reduction cycles contributed to both iron detoxification and improved soil buffering capacity (Rupngam & Messiga, 2024).

Interestingly, treatment A3, which extended the flooding duration to 3 weeks followed by 3 weeks of drying, exhibited the highest Fe^{2+} concentration at 30.6 ppm, demonstrating that prolonged reducing conditions promote excessive Fe^{2+} solubilization. While pH remained relatively stable (6.37–6.74), the extended flooding phase caused Fe^{2+} accumulation to exceed levels observed in other treatments, increasing the risk of chronic iron toxicity (Saidi et al., 2021).

The most notable results were observed in treatment A4, which involved 3 weeks of drying followed by 3 weeks of flooding. This treatment recorded the lowest Fe^{2+} concentration among the periodic flooding regimes, with an average of 4.08 ppm. The extended drying phases provided sufficient time for the oxidation of Fe^{2+} to Fe^{3+}, forming insoluble precipitates such as $Fe(OH)_3$ that significantly reduced the solubility of iron during flooding. The corresponding pH dynamics in A4, with a low of 5.53 during early phases but increasing during flooding to stabilize around 6.26, reflect the ameliorative effects of periodic oxidation and the accumulation of bicarbonates during reducing conditions (Karimian, 2017).

When compared to the initial soil characteristics, the results demonstrate the transformative impact of optimized water management on iron dynamics and pH stabilization. The initial pH of 4.70 and exchangeable Fe concentration of 4881 ppm highlight the inherent challenges of cultivating rice in Ultisol soils. Treatments like A4 effectively reduced Fe^{2+} concentrations to levels well below the initial soil conditions, while also elevating the pH to near-neutral levels. This improvement underscores the importance of balancing reducing and oxidizing conditions through extended drying intervals to mitigate iron toxicity and enhance soil health.

The findings of this study align with previous research emphasizing the role of periodic flooding in managing iron solubility in paddy soils (Saidi et al., 2021). Beyond its direct effects on Fe^{2+} solubility and pH stabilization, periodic flooding offers potential long-term environmental benefits. Compared to continuous flooding, periodic drying phases reduce methane (CH_4) emissions, a major greenhouse gas associated with anaerobic decomposition in flooded paddy fields (Wassmann et al., 2020). Additionally, alternating wet and dry cycles can enhance soil aeration, promoting microbial activity that supports nutrient cycling and long-term soil fertility. These benefits suggest that optimized flooding regimes not only improve rice productivity but also contribute to more climate-resilient and sustainable agricultural practices. The results underscore the need for future research on the cumulative effects of periodic flooding across multiple cropping cycles, particularly in marginal tropical soils where sustainable water management is crucial for maintaining soil health and reducing environmental footprints.

Responses of Growth and Yield Parameters of Rice (*Oryza sativa* L.)

Periodic flooding profoundly influenced the growth and yield parameters of rice cultivated on newly opened Ultisol soils, characterized by an acidic pH (4.70), high organic carbon content (14.3%), and elevated levels of exchangeable iron (4881 ppm). These inherent soil constraints necessitate careful water management strategies to mitigate iron toxicity and enhance rice productivity. The effects of different flooding and drying intervals on plant height, tiller number, panicle number, grain quality, and dry weights are summarized in Table 3.

The periodic flooding regimes significantly affected plant growth and productivity, as reflected in the data from Table 3. The initial soil characteristics of high acidity and Fe toxicity likely limited plant performance under continuous flooding (A0), which produced relatively low plant height (117.66 cm), tiller number (6.30), and panicle number (6.20). These findings suggest that constant submergence exacerbated reducing conditions, leading to higher Fe^{2+} solubility in the water column (2.01 ppm) and reduced oxygen availability, thereby restricting root growth and nutrient uptake (Ponnamperuma, 1972).

The most favourable results were observed in treatment A1, where alternating 2-week intervals of flooding and drying produced the tallest plants (126.80 cm), the highest tiller number (7.80), and the greatest panicle number (7.40). This treatment also resulted in the highest grain yield, with dry grain weight (DGW) reaching 25.0 g and milled grain weight (MGW) at 19.20 g. The shorter drying intervals in A1 likely facilitated the oxidation of Fe^{2+} to Fe^{3+}, reducing its solubility and toxicity while maintaining adequate soil moisture for optimal plant growth (Karimian, 2017). The relatively high percentage of filled grains (77.10%) in A1 further underscores the efficacy of this water management strategy in balancing vegetative and reproductive growth phases.

Conversely, treatment A2, which involved 2 weeks of drying followed by 2 weeks of flooding, resulted in significantly lower productivity. The dry grain weight (DGW) was only 13.9 g, the lowest among all treatments, and the percentage of filled grains dropped to 59.50%. These results suggest that the alternating water regime in A2 disrupted nutrient availability during critical growth phases, emphasizing the importance of precise water

Table 3
*Growth and yield parameters of rice (*Oryza sativa *L.) under periodic flooding (n = 5)*

Treatment	Plant Height (cm)	Tiller Number	Panicle Number	% Filled Grains	Dry Grain Weight (g)	Milled Grain Weight (g)	Weight of 100 Grains (g)
A0	117.66 b	6.30 a	6.20 a	75.20 b	23.8 c	17.40 c	19.00 a
A1	126.80 c	7.80 b	7.40 b	77.10 b	25.0 c	19.20 c	19.50 a
A2	117.41 b	7.00 ab	6.00 a	59.50 a	13.9 a	11.10 a	17.60 a
A3	120.50 b	7.50 b	6.70 ab	65.20 ab	18.8 b	14.50 b	18.10 a
A4	109.80 a	7.30 ab	6.70 ab	67.37 ab	17.2 ab	14.31 b	17.50 a

Note. Numbers followed by different letters in the same column indicate significant differences (DMRT, $p < 0.05$). Data = means management in high-Fe soils. Treatments with extended flooding or drying phases (A3 and A4) demonstrated mixed outcomes. While A3 achieved moderate plant height (120.50 cm) and tiller production (7.50), the prolonged flooding intervals likely increased Fe^{2+} solubility (30.6 ppm), negatively affecting yield components such as dry grain weight (18.8 g DGW) and percentage of filled grains (65.20%). Similarly, A4, with its extended drying phases, recorded the lowest plant height (109.80 cm) and reduced grain quality (67.37% filled grains and 14.31 g MGW), indicating that longer drying periods induced temporary moisture stress that offset the benefits of Fe detoxification.

These findings highlight the critical role of balanced flooding and drying intervals in mitigating Fe toxicity while maintaining soil moisture and nutrient availability. The effectiveness of A1 in enhancing growth and yield aligns with previous studies that emphasize the importance of periodic flooding in managing iron solubility and toxicity in paddy soils (Saidi et al., 2021). Beyond improving soil conditions and rice productivity, periodic flooding offers additional benefits for sustainable water management, as it reduces the need for continuous irrigation and helps optimize freshwater use, an increasingly critical factor in rice-growing regions facing climate variability and water scarcity (Ninin et al., 2024). The ability of this method to sustain high yields on Fe-toxic soils also has important food security implications, particularly in Southeast Asia, where rice is a staple crop for millions of smallholder farmers (Tan et al., 2019; Wu et al., 2019). Future research should explore the long-term effects of periodic flooding on soil nutrient dynamics, microbial activity, and scalability across diverse agroecosystems, ensuring that this approach can contribute not only to iron toxicity mitigation but also to climate-resilient and water-efficient rice farming systems on marginal soils.

CONCLUSION

This study demonstrates that periodic flooding significantly influences the growth and yield of rice (*Oryza sativa* L.) on newly opened Ultisol soils, which are characterized by high acidity (pH 4.70) and elevated Fe^{2+} concentrations (4881 ppm). Continuous flooding (A0) led to reduced growth and yield due to persistent iron toxicity, while the two-week flooding–two-week drying (A1) treatment produced the highest rice productivity, with improvements in plant height, tiller number, and dry grain yield. The alternating flooding-drying cycle in A1 effectively regulated Fe^{2+} solubility, stabilized pH, and mitigated iron toxicity, creating a more favourable soil environment. However, extended flooding (A3) resulted in excessive Fe^{2+} accumulation (30.6 ppm), whereas prolonged drying in A4 induced moisture stress, highlighting the importance of balancing oxidation-reduction processes. This study was conducted under controlled greenhouse conditions and a single growing cycle, which may not fully capture long-term soil transformations and field-scale variability. Future research should explore multi-season field trials, assess the long-term impact of periodic flooding on soil fertility, and evaluate its economic feasibility to ensure scalability in real-world rice production systems. While periodic flooding presents a promising water management strategy for enhancing rice productivity on iron-toxic Ultisol soils, further optimization is required to maximize its benefits across diverse tropical agroecosystems.

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