Unravelling of Soil pH Dynamics under Flooded Environment: A Review

P. Subramaniyan

Ph. D. Scholar, Dept. of Horticulture, SLS, CUTN, Thiruvarur

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Abstract— *Global climate change has increase the frequency and severity of extreme weather conditions including heavy rainfall followed by subsequent flooding. Soil pH is one of the most influential chemical parameters that have an impact on directly affecting the nutrient availability status, microbial activity and overall plant health. During the flooding period of paddy crop the soil pH for initially < 6.5 it was increased to approximately 7.0. Rice cultivated under continuous flooded conditions when soil pH became varied from 6.1 to 6.5 throughout the crop growth period. Agricultural crops such as rice benefit from mild increases of soil pH in submerged conditions to enabling improved nutrient solubility and reduced aluminum toxicity. In this contrast, crops like maize, wheat and legumes are inhibited the growth and nutrient uptake under flooded soil due to shifting of soil pH environments. Future research and development must focus on deeper understanding and management of these soil chemical shifts to ensure resilient cropping systems.*

Keywords— Agriculture, Climate change, Flooding, Nutrient, Soil pH and Rainfall.

I. INTRODUCTION

Global climate change has increase the frequency and severity of extreme weather circumstances with heavy rainfall followed by subsequent flooding. It is a direct effect of prolonged waterlogging and inundation stress altering soil physio-chemical and microbial changes in agricultural soils. Consequently, the understanding of how soil pH responds to these conditions has become critical. Flooding-related disruptions due to soil pH changes can lead to substantial agricultural losses. When soil pH shifts from the optimal range typically 6.0–7.0 for most crops, nutrient solubility becomes impaired, toxic elements may become bioavailable (e.g., aluminum, manganese) and microbial function is inhibited. Global estimated acid sulfate soils alone affect over 49 million hectares, predominantly in Asia. Where water management is key challenges cause significant crop failure due to post-flood pH depression (Dent, 1986). In India, economic losses due to reduced soil productivity under waterlogged and pH-altered conditions in lowland rice fields are estimated in the billions of rupees annually (Singh & Sharma, 2016). Horticultural crops like tomatoes, chillies, and bananas, which are particularly sensitive to pH changes, often exhibit stunted growth and fruit loss in these settings (Yadav *et al.,* 2017). Moreover, these losses are increased by input cost especially for lime application in acidic soils or sulfur amendments in alkaline soils and long-term degradation of soil fertility.

The most immediate effect of anaerobic soil conditions on plant is a reduction in aerobic respiration in roots. The particular end product of anaerobic respiration is partially dependent on soil pH. At a pH above neutrality, lactate fermentation is dominant, and as pH decreases (due to partially lactate fermentation), ethanol fermentation is induced. Rapid drop in cytosolic pH called acidosis is thought to be one of the main reasons why cells die in response to flood. In flood tolerant plants the pH drop may be counteracted by an alkaline process (Crawford *et al.* 1994).

Soil pH is one of the most influential chemical parameters that have an impact on directly affecting the nutrient availability status, microbial activity and overall plant health. Alteration of soil pH has a significant role on the sustainable cultivation of agricultural and horticultural crop production under flooded conditions. In this present review is mainly focused on critical examination of the mechanisms behind the modification of the soil pH under the flooding conditions. To assess the impact of soil pH changes on different crop species and explore soil management practices that mitigate adverse environmental effects

II. DIFFERENT TYPES OF SOIL AND PH CHANGES OCCURRED DURING FLOODED CONDITIONS

1) **In acidic soils (pH < 5.5) commen in the area of tropical regions having red or yellow and laterites soils are initially low pH or acidic nature. But, when flooded condition pH is increased. Because, when the flooded conditions** oxygen

is depleted through microbes begin reducing **Fe^{3+} to Fe^{2+} and Mn^{4+} to Mn^{2+}.** Hence, the reduction processes may **consume the hydrogen ions (H^+)** → leads to a **rise in pH. Ponnamperuma (1984) reported i**n tropical India and Southeast Asia, paddy cultivated in the acidic red soils which showed an increase from pH 4.5 to pH 6.2 during the growing season.

2) Arid/semi-arid zones, calcareous soils, vertisols **are i**nitial pH is high alkaline **(pH > 7.5 and** pH trends during the flooding m**ay be decreased. In the f**looded soil accumulates **CO_2**, which dissolves in water to form **carbonic acid (H_2CO_3) its having** slightly **low** acid pH. If sulfur compounds are present (e.g., gypsum), **sulfate reduction** can increase alkalinity again later. *Abou El-Naga et al., 2019 noticed that the p*arts of Egypt's Nile Delta, pH in calcareous soils dropped from 8.1 to 7.4 during extended flooding durations.

3) **Neutral soils having** alluvial plains and many productive crop lands initially near neutral pH **(pH ~6.5–7.5)** at the time of flooding mild fluctuation which was happened. Those soils have **moderate buffering capacity** due to clay minerals and organic matter. The pH may be initially dropped slightly due to CO_2, then increase slightly as Fe and Mn reduction occurred. Often stabilizes around **pH 6.5–7.0**, ideal for rice crop. In Indo-Gangetic plains of India, neutral loamy soils showed pH variation only between 6.7 and 7.3 under flooding condition *(Sahrawat, 2003).*

4) **Peaty and organic soils commonly found in m**arshes, peatlands, lowland of tropics. In the initial pH was often slightly acidic (pH 5–6). The pH is during flooding period c**an raise**, but post-drainage time **sharply dropped. U**nder flooding condition reduction of Fe/Mn cases **pH id increased.** After drainage, o**xidation of sulfides** (especially pyrite FeS_2) produces **sulfuric acid** → severe acidification (pH < 4). These soils become **toxic for crops after drying** unless properly managed. *Minh et al., 2008 reported in* Vietnam's Mekong Delta, acid sulfate soils increased to pH 6.0 under flooding then dropped to pH 3.8 upon drainage.

5) **In the saline and sodic soils of c**oastal zones, arid inland regions, initial pH is often > 8.0. Flooding duration pH became c**omplex in nature.** Flooding can **leach soluble salts**, reducing pH slightly. But in sodic soils, poor structure leads to clay dispersion → **low permeability**, **stagnant water**, limited leaching. Without leaching, **pH remains high** unless gypsum or acid-forming fertilizers are added In western India, sodic soils flooded for rice showed only minor pH decline (8.6 to 8.2) unless amendments were applied *(Sharma & Gupta, 2005).*

TABLE 1
SOIL TYPE VS. PH CHANGE UNDER FLOODING CONDITIONS

S. No.	Soil type	Initial soil pH	Flooding effect on soil pH	Cause
1	Acidic lateritic soils (e.g. Ultisols, Oxisols)	4.5–5.5	Increases	Iron (Fe^{3+}) and manganese (Mn^{4+}) are reduced to Fe^{2+} and Mn^{2+}, consuming H^+ ions and increasing pH.
2	Alkaline soils (e.g. Aridisols, Calcareous)	>7.5	Soil pH decreases (slight)	CO_2 accumulation followed by carbonic acid and also ammonia accumulation
3	Neutral loamy soils (e.g. Mollisols, Alfisols)	6.5–7.5	Minor soil pH changes occurred during the flooding	Balanced buffering from clay/OM and Buffering capacity keeps stabilized soil pH; redox changes may mildly alter nutrient solubility.
4	Peaty/acid sulfate (Histosols)	~5.5	Increase/ more acidic under flooding, decrease after drainage	Sulfide oxidation reduction take place post flooding; pyrite oxidation after drainage (↓)
5	Sodic saline soils	8.5–10	Initially pH may be decreased then rebound after flooding	Low permeability; clay dispersion and exchangeable sodium reactions; limited leaching
6	Clayey soils (Vertisols)	6.0–8.0	pH changes slowly	High buffering capacity and shrink-swell clays delay redox equilibrium.
7	Sandy soils (Entisols)	On the flooding occasions soil pH varied from often acidic in nature	Rapid but limited pH shifts	Low buffering capacity, fast water movement and fewer redox-active minerals.

III. MECHANISMS OF SOIL PH CHANGE UNDER FLOODED CONDITIONS

When flooded conditions, soil become transition from aerobic (oxygen-rich) to anaerobic (oxygen-depleted) environment. This shift triggers a series of redox reactions activities that significantly influence in soil pH. One of the primary mechanisms is the reduction of iron and manganese oxides. Under anaerobic conditions, iron (Fe^{3+}) and manganese (Mn^{4+}) oxides are biologically reduced to their soluble forms, Fe^{2+} and Mn^{2+}, respectively. The reduction of ferric iron (Fe^{3+}) can be represented as,

$$Fe^{3+} + e^- \rightarrow Fe^{2+} \quad (1)$$

Similarly, manganese reduction occurs as,

$$MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O \quad (2)$$

These reactions consume hydrogen ions (H^+), thereby reducing acidity and causing a rise in soil pH, especially in acidic soils (Ponnamperuma, 1972).

A second major mechanism is nitrate reduction via microbial de-nitrification. In the absence of oxygen, facultative anaerobic bacteria use nitrate (NO_3^-) as an electron acceptor, reducing it to gaseous forms like nitrogen (N_2) or nitrous oxide (N_2O). The representative de-nitrification reaction is,

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad (3)$$

This process also consumes protons (H^+), further it was increasing soil pH under flooded condition (Tiedje, 1988). De-nitrification process is common in waterlogged agricultural soils and significantly affects nitrogen availability and pH dynamics.

Another important factor is the accumulation of ammonium (NH_4^+). Under normal aerobic conditions, ammonium is oxidized to nitrate via nitrification, a process that releases H^+ and acidifies the soil. However, in flooded soils, oxygen is limited, and nitrification is suppressed. Consequently, ammonium accumulates:

$$\text{Organic N} \rightarrow NH_4^+ \quad (4)$$

While NH_4^+ is slightly acidic, its accumulation under flooded conditions may lead to a slight decrease in pH, although this effect is typically overshadowed by the pH-increasing reactions described above (Patrick & Reddy, 1976).

In calcareous soil, flooding leads to form carbonate dissolution, which acts as pH buffer. Microbial respiration under anaerobic conditions produces CO_2, which dissolves in water to form carbonic acid:

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \quad (5)$$

This weak acid reacts with calcium carbonate ($CaCO_3$),

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \quad (6)$$

This reaction neutralizes acidity and maintains or slightly raises pH in alkaline soils (Sah & Mikkelsen, 1986).

Anaerobic decomposition of organic matter also plays a crucial role in soil pH. Initially, this process generates short-chain organic acids (e.g., acetic, butyric acids), which can temporarily reduce pH. However, as decomposition continues, microbial by-products such as bicarbonates (HCO_3^-), ammonia (NH_3), and hydroxides (OH^-) accumulate,

$$\text{Organic matter} + \text{microbes} \rightarrow CH_4 + CO_2 + HCO_3^- + NH_3 \quad (7)$$

The net effect over time is typically an increase in soil pH, particularly in soils with high organic matter (Ponnamperuma, 1984).

In sulfate-rich soils, sulfate-reducing bacteria (SRB) contribute to pH regulation by converting sulfate (SO_4^{2-}) into hydrogen sulfide (H_2S),

$$SO_4^{2-} + 8e^- + 8H^+ \rightarrow H_2S + 4H_2O \quad (8)$$

Hydrogen sulfide reacts with iron to form insoluble iron sulphide,

$$H_2S + Fe^{2+} \rightarrow \text{FeS (precipitate)} \quad (9)$$

This reaction removes acidic components and contributes to a rise in pH in reduced soils (Patrick & De Laune, 1977).

In flooded conditions initiate a cascade of redox transformations in soil that predominantly result in a rise in pH, especially in acidic soils. While processes like ammonium accumulation and organic acid production may initially lower pH, dominant mechanisms such as iron/manganese reduction, nitrate reduction, carbonate dissolution, and sulfate reduction typically outweigh them in the long term. The final impact on soil pH is governed by the soil's original pH, redox status, microbial populations, and organic matter content. Mechanism of flooding is essential for sustainable soil and crop management in flood prone regions.

TABLE 2
SOIL PH CHANGE AND NUTRIENT STATUS UNDER FLOODING CONDITIONS

S. No.	Electron acceptor	Reaction	Effect on soil pH	Approximate time after flooding
1	Nitrate (NO_3^-)	Denitrification to N_2 gas	Releases H^+ → lowers pH	1–3 days
2	Manganese (Mn^{4+})	Reduced to Mn^{2+}	Consumes H^+ → raises pH	3–7 days
3	Iron (Fe^{3+})	Reduced to Fe^{2+}	Consumes H^+ → raises pH	7–14 days
4	Sulfate (SO_4^{2-})	Reduced to H_2S gas	Slight H^+ use, but H_2S toxic	2–3 weeks
5	CO_2 (Carbon dioxide)	Methanogenesis → CH_4 gas	Neutral/slightly alkaline	3–4 weeks and beyond

IV. FACTORS INFLUENCING SOIL PH CHANGES DURING FLOODED CONDITIONS

Flooding drastically alters the soil's chemical environment and the pH which shift during and after flooding depends on interacting between soil **physical, chemical, biological and environmental** factors. The following factors that influence the soil pH under flooded conditions,

1) **Soil Redox Potential (Eh):** The soil redox potential is a measure of the soil's oxidation-reduction status. It affects soil pH as redox potential drops (becomes more reducing), protons are consumed in redox reactions, often increasing pH in acidic soils (Ponnamperuma, 1972).

   Chemical process: Oxygen reduction → NO_3^- reduction → Mn^{4+} reduction → Fe^{3+} reduction → SO_4^{2-} reduction → Methanogenesis.

2) **Soil organic matter content:** Soils having more organic matter equally contain more microbial activity (Reddy and De Laune, 2008)**.** When reduction processes taken place which consume H^+ ionic potential to increasing soil pH. But, excessive decomposition of post-drainage time can acidify the soil due to sulfur or organic acid accumulation.

3) **Duration and depth of flooding:** there are three different categories in the flooding was reported by Sahrawat (2004).
   a. **Short-term flooding**: Causes minor, often reversible pH changes.
   b. **Prolonged flooding**: Promotes stronger reduction reactions, more dramatic pH shifts and
   c. **Deep vs. shallow waterlogging** is affects oxygen diffusion and microbial stratification.

4) **Soil texture and type:**
   a. **Clay soils**: High buffering capacity; slower pH changes.
   b. **Sandy soils**: Quick but limited pH changes; poor buffering.
   c. **Peaty soils**: Can become very acidic after drainage due to sulfide oxidation Brady & Weil (2008).

5) **Temperature:** When soil temperature during the flooding occasion can influences microbial metabolism. The high temperature due to accelerates redox activity reactions and cold soils are delay pH changes due to slower microbial activity (Fageria *et al.,* 2010).

6) **Type of crops grown:** Under the flooded condition some crops like rice can modify rhizosphere pH through oxygen transport and root exudates. Legumes are sensitive to low pH, affecting nodulation and N-fixation. Deep-rooted vs shallow-rooted crops experience different pH zones (Kirk, 2004).
7) **Microbial community composition:** Mitsch & Gosselink (2015) reported that the anaerobic microbes dominate under flooded conditions and enzyme activities also shifts, altering organic acid production. Their respiration products (e.g., NH_4^+, CH_4, H_2S) affect soil pH either by consuming or producing protons.
8) **Presence of acid sulfate minerals:** Dent (1986) studied the acid sulphate soils after flooding the oxidation of FeS_2 leads to release of sulfuric acid → severe drop in pH (<4) and often found that coastal and deltaic soils (e.g., Pyrite, Mekong, Sundarbans)
9) **Fertilizer and amendment history:** Pre-flooded conditions the fertilizer types either nitrate vs. ammonium can affect soil pH trajectory. Lime/amendment residues buffer pH differently in flooded vs non-flooded soils (Fageria and Baligar, 2003).
10) **Repeated flooding and drainage cycles:** Repeated flooding and drying can cause cyclical pH swings (e.g., Paddy-upland rotation systems: rice-wheat, rice-legume) (Singh and Ladha, 1977).

V. INFLUENCE OF SOIL PH AND FLOODING DYNAMICS ON THE PERFORMANCE OF AGRICULTURE AND HORTICULTURAL CROPS

According to the IPCC, 1966 year report, flooding causes the increase soil pH in acidic soil and decrease in alkaline soil. The primary cause of the pH rise in acidic soils is the conversion of acidic Fe^{3+} to Fe^{2+}, which also lowers the Eh. Soil pH of both acidic and alkaline soils tends to converge around neutral after flooded conditions (Ponnamperuma, 1972). Whereas, Crowley soil with an initial pH of 5.7 to it was gradually increased after being flooded/submerged condition around soil pH of 6.9.

According to Abdullahi *et al.* (2011), flooded soil had a pH range varied from 5.97 to 6.28 and was fairly acidic. Akter *et al.* (2011) also revealed the finding of result showed pH (water) value of soils ranged between 5.4 un-flooded conditions and it was increased flooded condition around 7.0. Because, release of silicon and sesquioxides from disintegration of clay lattice from seasonal flooding and doughtiness. Due to their silica-rich parent materials (acidic to intermediate crystalline rock) which was found in majority of flooded soils of Nigeria are to be acidic pH 5.5 or less (Isah, 2017; Aliyu, 2011). Nancy (2011) stated that pH were greater in flooded soils compared to non-flooded soil. On the other hand, Vincent *et al.* (2014) established that the control soil (well drained) is weakly alkaline than those of the flood affected farmland areas. Jusop *et al.* (2014) recorded that the post effect of flooding on affected farmlands was evident in the reduction in pH values, tending the soils towards acidity.

Sani Idris (2019) studied the three different soil depth viz., 0–30cm, 30-60 cm and 60-90cm under seasonally flooded field (SFF) and non-flooded field (NFF).

Two techniques were employed to measure the pH of the soil to water (1:2.5); soil to CaCl2 solution (1:2.5). Among the method taken into consideration, soil pH values of 5.93, 5.29(0-30cm), 6.41, 5.67(30-60cm) and 7.03, 6.26 (60-90cm) were found in SFF it was significantly higher than NFF soil pH of 5.663, 4.85(0-30cm), 6.12, 5.52(30-60cm) and 6.65, 5.96 (60-90cm). The presence of more exchangeable basic cations, which may have been deposited by flood water from the upland areas due to the pH increase, and the higher amount of organic matter complexes in SFF, which can buffer soil acidity. Similarly kind of result were obtained under acidic conditions of flooded soils (Idoga, 2006; Egharevba and Mayah, 2001; Brady and Weil, 1999; Miller and Donahue, 1992).

Soil pH of the paddy crop during flooding phase it was increased from less than 6.5 to about 7.0. Whereas, rice was grown in continuously flooded conditions with soil pH ranging from 6.1 to 6.5 (Ding *et al.*, 2019). Kashem and Singh (2001) reported that the soil pH during flooding time increased. The soil pH increased by roughly 2.0, 1.0, and 0.6 units in the tannery, city sewage and alum shale soils for rice (*Oryza sativa* L.) throughout the 65-day submersion condition.

While rice (*Oryza sativa*) is naturally adapted to low-pH flooded environments and many legumes crops, vegetables and fruit trees are exhibit reduced growth, nutrient uptake and yield when subjected to acidic or alkaline deviations from their optimal pH ranges (Marschner, 2012; Fageria *et al.,* 2011). A major challenge lies in understanding how different soil types and soil pH fluctuations under flooding conditions to tailoring crop choices and management strategies accordingly.

In the flooded soil, rice soil at a sample depth of 15 cm the pH varied from 4.5 to 5.2 (Schulz *et al*., 2024). The pH conditions' geographical heterogeneity decreased over the next few weeks. The pH rose throughout the course of 16 weeks, ranging from 6.0 to 6.2.

For problematic soils, flooding is an excellent way to neutralize pH it was reported by Rangasami *et al*., 2022. The release and availability of plant nutrients are after floods, often positively induced by the neutralization activity of acidity in acid soils and alkalinity in alkaline soils. Wetland rice can better absorb nutrients from soils with a neutral pH, which can be achieved by adding or retaining a moderate amount of organic matter. Because of their decreased solubility due to elevated pH, toxic quantities of Al and Mn in soil solution are lowered.

Zheng and Zhang (2011) investigated three distinct moisture regimes in paddy cultivated soils. The Soil pH was 5.06, 5.08 and 5.81 under 75% field capacity, wetting drying cycle and flooding regimes during the initial stage. It was changed that the soil pH is increased from 5.81 (day 5) to 6.69 (day 150) under flooding regime with an increment of 0.88 units. When biological and microbiological processes in wet paddy soil are coupled with restricted oxygen diffusion and/or depleted, reducing conditions. This leads to a notable shift of soil pH increase towards neutrally and decrease in Eh (Narteh and Sahrawat, 1999).

Borin *et al*. (2016) reported that the initial soil pH value of the experimental region was originally very low 4.2 and when the flooded condition increasing in soil pH values of rice field which observed since 21 days after flooding existence around 6.2. In contrast of 61 days after flooding, the pH of the soil in the Cl-treated field samples reached about 6.8. In acidic soils, where Fe oxides are the main oxidants, even that exist the proton release due to CO_2 dissociation and rhizosphere oxidation, the H^+ consumption is higher than the release of soil pH increase up to7.0 (Sousa *et al.,* 2009).

According to Gambrell and Patrick (1978) reported that the soil pH of the mango cultivar "Tommy Atkins" was initially 7.4, which was indicative of anaerobic soil conditions within three days of flooding. The pH reduced around 7.0 after 21 days of flooding (Larson and Schaffer, 1991).

Cao *et al.,* 2020 reported that the soil pH under NF soil was 6.71, while in the rhizosphere of *Salix integra*, Cu stressed flooded soils significantly increased in soil pH of 6.83–6.89.

The effects of organic materials in the soils of Geriyo irrigation project were studied by Solomon *et al.,* 2014. They found that applying organic materials like poultry droppings generally increase the soil pH about 8.2 under submerged conditions. The soil pH was increased by these organic anion is consumption of protons. For this elevated soil pH is increased could be exchange of protons (H+) between the soil and when adding organic materials (Tang *et al*., 1999).

TABLE 3
HORTICULTURAL CROP RESPONSES TO FLOODING-INDUCED PH CHANGES

S. No.	Crop	Flooding response	pH sensitivity range	Impact
1	Tomato	Root rot, Fe toxicity in low pH soils	6.0–6.8	Chlorosis, poor yield
2	Potato	Soil pH drop and oxygen stress due to tuber cracking	5.5–6.5	Internal browning
3	Onion	Poor growth in acidic, waterlogged soils	6.0–6.8	Poor bulb formation, rot
4	Cabbage	Tolerates slight flooding, but not low pH	6.0–7.0	Leaf malformation, slow heading
5	Mango	Sensitive to root pathogens in flooded soils	6.0–7.5	Collar rot, low flowering
6	Banana	Root suffocation in poorly drained soils	5.5–6.5	Stunted growth, pseudostem rot
7	Citrus	Decline in Fe, Zn at high pH; root asphyxiation	5.5–7.0	Yellowing, dieback

TABLE 4
SOIL TYPE, EFFECT OF SOIL PH AND CROP RESPONSES UNDER FLOODED CONDITIONS

S. No.	Soil type	Crop(s)	Flood effect on soil pH	Notable observations under flooded conditions	Reference
1	Alluvial, Lateritic	Rice	Increase soil pH from ~5.2 to ~6.5	Fe/Mn reduction increased pH	Poonia & Ponnamperuma (1976)
2	Alfisols	Rice	Increase soil pH from acidic to near neutral	Denitrification reduces acidity	Singh & Tripathi (2008)
3	Calcareous, clayey	Rice and Wheat	Stable soil pH near to neutral pH	Buffering capacity of soil due to carbonates	Yaduvanshi *et al.* (2005)
4	Acid sulfate	Rice	Increase soil pH during flooded condition, decrease soil pH below 4 after drainage	Pyrite oxidation post-flooding	Minh *et al*. (2012)
5	Silt loam	Rice and Jute	Increase soil pH up to 6.8 under flood	Better Phosphorus availability, reduced Al toxicity	Islam *et al*. (2014)
6	Vertisols	Soybean, Maize	Increase soil pH under temporary flooding	Reduced O_2 triggers acidification	Reddy & Delaune (2008)
7	Peaty soils	Vegetables and Pasture	Decrease soil pH due to organic acid accumulation	Anaerobic decay increases acidity	Koerselman *et al.* (1993)
8	Sodic clay	Cotton	Decrease soil pH due to Fe/Mn reduction	Improved micronutrient solubility	McKenzie *et al.* (2004)
9	Red sandy loam	Groundnut	Stable soil pH during short floods	High soil buffering capacity	Sreenivas *et al.* (2013)
10	Peaty wetland	Taro, Banana, Coconut	Decrease under stagnant water	Soil organic matter fermentation enhances acidification process	Nair *et al.* (2008)
11	Saline-sodic clay	Rice and Pulses	Increase soil pH upto ~7.2 during flooding, decrease when post-flooded conditions	Stabilized soil pH under rice; pulses affected by acid shock	Natesan *et al.* (2010)
12	Black clay loam	Banana, Turmeric, Tapioca	Decrease soil pH from 6.5 to 5.5	Increased root rot risk, micronutrient imbalance	Jayakumar et al. (2016)
13	Sandy/red lateritic soils	Tomato and Brinjal	Decrease soil pH from 6.8 to 5.3	Poor drainage slowed pH recovery	Loganathan et al. (2018)
14	Clay loam	Coconut and Arecanut	Decrease soil pH from 6.3 to 5.0	Root hypoxia, increased sulfur stress	Nair & George (2007)
15	Acid sulfate coastal soil	Rice, Chilli and Sunflower	Decrease soil pH up to < 4 post-drainage	Acid sulfate soils highly reactive upon drying	Subramanian & Thiyagarajan (2005)

VI. SOIL PH MANAGEMENT STRATEGIES UNDER FLOODED CONDITIONS

Soil pH management under flooded conditions is crucial for optimizing crop yield and health, as pH influences nutrient availability, microbial activity, and soil structure. The fluctuating pH levels during flooding—due to anaerobic conditions—can be detrimental or beneficial depending on the crop type and soil properties. Effective management strategies help mitigate adverse pH changes, improving crop productivity in flood-prone agricultural areas.

6.1 Water management practices:

1) **Alternate wetting and drying (AWD)**: AWD is a widely practiced water management strategy for rice cultivation, especially in areas with limited water resources. It involves alternate wetting and drying of rice fields rather than continuous flooding. This method helps regulate pH by preventing continuous anaerobic conditions that could lead to excessive acidification of the soil. Studies show that AWD can reduce methane emissions, limit the reduction of iron and manganese, and stabilize soil pH (Gao et al., 2018).

2) **Controlled drainage**: Controlled drainage systems, which allow for the controlled release of water after flooding, can help restore soil oxygen levels, thus regulating microbial activity and preventing drastic pH shifts. This practice is particularly beneficial in regions prone to waterlogging (Kowalska et al., 2021).

3) Soil amendments:

   a. Lime application: The addition of lime (calcium carbonate) is a common strategy for neutralizing acidic soils. In regions where flooding leads to soil acidification (e.g., due to the reduction of iron and sulfur compounds), liming can raise the pH to levels that are more favorable for crop growth. This is particularly important in rice paddies, where flooding promotes the formation of sulfuric acid in the soil (Sharma & Saha, 2017). The use of lime helps in maintaining an optimal pH range (5.5-7) for most crops.

   b. Organic matter addition: Incorporating organic matter (compost, manure) into soils before and after flooding can help buffer pH changes by increasing soil buffering capacity. Organic amendments also encourage microbial diversity and promote the activity of beneficial microorganisms that can mitigate the negative effects of acidic conditions (Schipper et al., 2019).

4) Selection of crop varieties:

   a. **Flood-tolerant crops**: Selecting crop varieties that are more tolerant to pH fluctuations and waterlogged conditions is another important strategy. Rice, for instance, has developed physiological mechanisms, such as aerenchyma (air spaces in roots), which allow it to thrive in low oxygen environments typical of flooded conditions. However, other crops like maize or legumes may suffer if soil pH falls below optimal levels (Becker et al., 2020).

   b. **Leguminous crops and pH sensitivity**: Leguminous crops are particularly sensitive to pH fluctuations, especially if pH drops below 5.0. Choosing varieties that are more resistant to pH-induced stress can help optimize yield in flood-prone regions (Patil et al., 2021).

5) Microbial activity and redox management:

   a. **Microbial management**: Microbial communities play a significant role in regulating soil pH under flooded conditions. Denitrification and methane production in anaerobic environments often lead to acidification, while the reduction of iron and manganese can increase soil pH. Managing microbial activity through proper soil management practices, such as the use of bio-inoculants, can help stabilize pH fluctuations (Smith et al., 2017).

   b. **Inoculation with nitrifying bacteria**: Inoculating soils with nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, can help balance the nitrogen cycle, thus reducing the accumulation of ammonium and preventing acidification (Sullivan *et al*., 2018).

6) Monitoring and adjusting soil pH:

   a. **Regular pH monitoring**: Regularly monitoring soil pH during flooding events is essential to detect early signs of pH fluctuations. Soil testing at different stages of crop growth allows for timely intervention using appropriate amendments. Automated pH monitoring systems can help farmers track pH levels in real time and adjust water management practices accordingly (Rasmussen *et al.*, 2020).

   b. **Fertilizer management**: Fertilization practices should be adapted based on the soil pH and the nutrient requirements of the crop. For instance, applying ammonium-based fertilizers in flooded fields with acidic soils may exacerbate pH reduction. Instead, ammonium nitrate or urea may be preferred in such scenarios, as they are less likely to contribute to soil acidification (Nandal et al., 2019).

VII. CONCLUSION

Flooding alters the soil environment drastically and one of the most significant consequences is shifting of soil pH due to oxygen depletion and redox reaction activities. Under flooded conditions, soils transition from aerobic to anaerobic condition to prompting a cascade of microbial and chemical changes that impact nutrient availability based on soil pH status (Ponnamperuma, 1984; Reddy & Delaune, 2008). The direction of pH change occurring, whether increasing or decreasing the soil pH depends on soil type, initial pH, soil buffering capacity and the duration including frequency of flooding (Patrick & Delaune, 1977). Whereas, the acidic soils are typically experience a temporary increase of soil pH due to proton consumption during reduction reaction process, while alkaline soils may acidify due to organic acid production and CO_2 accumulation (Brady & Weil, 2017).

Agricultural crops such as rice benefit from mild increases of soil pH in submerged conditions to enabling improved nutrient solubility and reduced aluminum toxicity. In this contrast, crops like maize, wheat and legumes are inhibited the growth and nutrient uptake under flooded soil due to shifting of soil pH environments (Setter & Waters, 2003). The effects on nutrient solubility such as iron, manganese, phosphorus and sulphur are sensitive to soil pH, leading to either deficiencies or toxicities depending on the redox-pH dynamic potential (Fageria et al., 2011). This emphasises are the importance of managing soil pH to sustain crop productivity during and after flooding events.

Horticultural crops, which generally require soil pH for optimal growth. The crops like tomatoes, citrus, grapes and peppers show chlorosis, stunted growth or even plant death when pH moves outside optimal threshold level (Ehret *et al*., 2010; Zhang *et al.*, 2019). In addition, microbial shifts in the rhizosphere also affect nutrient cycling and disease susceptibility in these high-value crops. Flooding not only changes the crop root-zone soil pH but also alters beneficial symbiotic microorganism such as mycorrhizae and rhizobia, which are crucial role in nutrient uptake in many horticultural crops (Kozlowski, 1997).

To mitigate these effects, strategic management practices such as lime application, raised beds, controlled drainage and the use of pH-tolerant crop varieties are essential for maintain the soil pH. Also monitoring real-time soil redox activities and soil pH changes can guide fertilizer application and drainage strategies to minimize long-term degradation (Pezeshki, 2001; Sharma *et al*., 2005). This is more helpful for understanding the dynamic relationship between soil pH, flooding and crop responses for ensuring resilient agricultural and horticultural systems in flood-prone conditions.

VIII. FUTURE PROSPECTS

Future prospects of soil pH under flooded conditions in agricultural and horticultural crop cultivation.

In the global climate change has marked by increasing frequency and intensity of rainfall pattern is making flooding or waterlogging is more common in many agricultural crop cultivated lands. One of the key challenges under these conditions is the rapid and often unpredictable fluctuation of soil pH. Future research and development must focus on deeper understanding and management of these soil chemical shifts to ensure resilient cropping systems (Ponnamperuma, 1984; Reddy & Delaune, 2008).

One of the most promising areas lies in advanced soil monitoring technologies. Precision agriculture tools, especially Internet of Things (IoT)-enabled soil sensors, now offer the possibility of continuously monitoring soil pH, redox potential (Eh) and moisture in real time. These tools could allow farmers to respond to unfavorable soil pH shifts with lime or sulfur applications, drainage modifications or chancing of fertilization schedules. Additionally, artificial intelligence (AI) models could predict soil pH trends based on real-time flooding events, enabling proactive soil pH correction strategies (Gebbers & Adamchuk, 2010; Sudduth *et al.*, 2013).

Breeding of agriculture and horticulture crops varieties which more scope for flood-resilient and pH-tolerant are another critical path. In the case of rice, extensive studies have shown its unique adaptations like aerenchyma formation and root oxygenation. These traits, along with rhizosphere acid–base balancing mechanisms, need to be bred into other cereals and horticultural crops like tomato, citrus and eggplant. Modern genomic tools, especially CRISPR/Cas9, offer the potential to accelerate development of such crops by targeting genes related to pH tolerance, nutrient uptake under flooding and organic acid metabolism (Setter & Waters, 2003; Zhang *et al*., 2019; Chen et al., 2019).

Finally, there is a need for policy support and farmer-level capacity building. Flood-induced soil pH stress is often underappreciated at the policy level and many farmers are unaware of how waterlogging changes soil chemistry. Governments and institutions must invest in farmer training, soil testing infrastructure and incentives for adopting sustainable water and soil pH management practices. Focused research on local soil types and crop responses to flooding across different agro-ecological zones will be crucial in forming future flooding issues eradication strategies (FAO, 2020).

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