Fertility and organic matter in submerged rice soils

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Wetland rice systems in Asia make a major contribution to global rice supply. The system is also able to maintain soil fertility on a sustainable basis. The essential components of wetland rice culture comprise cultivation of land in the wet or flooded state (puddling), transplanting of rice seedlings into puddled rice paddies, and growing the rice crop under flooding. The land is dry or flood-fallowed during the turnaround period between two crops. Following these cultural practices, two or three crops of rice or rice with upland crops in sequence are grown. However, in the present context of increasing freshwater scarcity, there is a case to shift from the traditional way of growing rice to ways that are water-wise. In this context, it is crucial that the benefits of the wetland rice system on soil fertility and productivity are considered. This article examines the benefits of growing rice in flooded conditions on soil fertility and its maintenance. Research has shown that the wetland rice system (growing rice in submerged soils) has a great ameliorative effect on chemical fertility: largely by bringing pH in the neutral range, resulting in better availability of plant nutrients and accumulation of organic matter. The article concludes that the benefits of growing rice using submerged conditions must be considered and weighed in the context of a likely shift to growing rice with water-management practices that are water-wise.

SOIL fertility and nutrient supplying capacity of a soil can be maintained on a long-term basis only by replenishing, by addition through external inputs, nutrients removed by cropping and those lost through physical, chemical and biological processes. In addition to replenishing plant nutrients, the application of organic matter is also crucial for maintaining fertility of soils. Soil organic matter acts as a reservoir of plant nutrients. The maintenance of a threshold level of organic matter in the soil is crucial for maintaining physical, chemical and biological integrity of the soil and also for the soil to perform its agricultural production and environmental functions[1].

Microbial activity in a soil drives organic matter decomposition and mineralization processes, leading to release of organically bound plant nutrients in forms available to growing plants. Because of the prevailing high temperatures in the tropical regions, decomposition or destruction of added and soil organic matter is relatively rapid. The balance between inputs and outputs of organic matter is the observed organic matter in a soil. Hence, the maintenance of soil organic matter is possible only through addition of organic matter on a continuing basis[2].

Wetland rice systems in Asia are making a major contribution to global rice supply[3]. These systems are also excellent examples of sustainable soil fertility maintenance[4]. A unique feature of soils that remain flooded for prolonged periods, for example soils that are used for continuous lowland rice cultivation, is the maintenance of soil fertility and productivity of wetland rice-based production systems[5].

Upland-based production systems have a greater tendency for unsustainability due mainly to relatively rapid loss of organic matter, degradation of soil fertility and deterioration in physical, chemical and biological properties[5].

Several studies indicate that given similar climatic and soil conditions, organic matter accumulates preferentially in tropical wetland rice soils compared to upland-based production systems. The maintenance of soil organic matter status in soils with tropical upland conditions is more difficult than in soils used for wetland rice conditions. The results from long-term studies of soil organic matter dynamics in upland and wetland rice-based production systems support this conclusion[6]. Under similar soil and climatic conditions, the maintenance of organic matter and fertility would seem more feasible in wetland rice than in upland rice-growing conditions.

The traditional way of growing lowland rice involves land preparation by cultivation of the land in flooded or wet state (puddling), followed by transplanting rice seedlings into the puddled rice paddies and growing the crop in a submerged condition.

Although the traditional method of growing lowland rice has been sustainable, the system uses high amounts of water. Critics argue that lowland rice should be cultivated with increased water use efficiency. Obviously, there is an urgent need to critically review and analyse the benefits of growing rice in submerged conditions in the context of soil chemical fertility amelioration and fertility maintenance, which might be affected by switching from traditional to water-saving methods.

This article reviews the recent literature and highlights the underlying principles that govern the maintenance of organic matter and soil fertility in wetland rice systems.

Submerging soil and chemical fertility

The most important influence of submerging a soil in water is to reduce oxygen supply. As a result, the entrained oxygen

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is quickly exhausted. The lack of free oxygen or anaerobiosis causes soil reduction and sets in motion a series of physical, chemical and biological processes. The influence of flooding on physical, chemical and electrochemical properties of soil has been comprehensively researched and reviewed from time to time[4,7–13].

The main electrochemical changes that influence the chemistry and fertility of submerged soils and growing of crops such as wetland rice include:

- A decrease in redox potential (redox potential, Eh) or reduction of the soil.
- An increase in pH of acid soils and a decrease in pH of alkali soils, and changes in the floodwater pH.
- An increase in specific conductance and ionic strength of soil solution.
- Ionic equilibria influence sorption–desorption reactions and the availability of major and micronutrients.

Submerging aerobic soils in water decreases its Eh that drops and stabilizes at a fairly stable range of + 200 mV to –300 mV depending on the soil, especially the content of organic matter and reducible species (nitrate, sulphate and ferric iron), particularly iron. But Eh of the surface water and the first few millimetres of top soil in contact with the surface water remain relatively oxidized in the Eh range of + 300 to + 500 mV[8]. A range of Eh is encountered in various soils from well-drained, aerated to waterlogged conditions (Table 1).

Table 1. Oxidation–reduction potential found in rice soils ranging from well-drained to submerged conditions[30]

Soil water condition	Redox potential (mV)
Aerated or well-drained	+700 to +500
Moderately reduced	+400 to +200
Reduced	+100 to –100
Highly reduced	–100 to –300

The Eh of soils controls the stability of various oxidized components [oxygen, nitrate, manganese (Mn IV), ferric (Fe III) iron, sulphate (SO_4^{2-}), carbon dioxide] in submerged soils and sediments (Table 2).

Table 2. Redox potentials in which the main oxidized components in submerged soils become unstable[30]

Reaction	Redox potential (mV)
O_2–H_2O	+380 to +320
NO_3–N_2, Mn^{4+}–Mn^{2+}	+280 to +220
Fe^{3+}–Fe^{2+}	+180 to +150
SO_4^{2-}–S^{2-}	–120 to –180
CO_2–CH_4	–200 to –280

The pH of acidic soils decreases following submergence because under anaerobic conditions, ferric iron is used as an electron-acceptor for oxidizing organic matter and during this process acidity is neutralized:

$$Fe_2O_3 + 1/2CH_2O + 4H^+ = 2Fe^{2+} + 5/2H_2O + 1/2CO_2. \quad (1)$$

In these redox reactions, ferric iron (from amorphous ferric hydroxides) serves as an electron-acceptor and organic matter (CH_2O) as the electron-donor. This reaction results in the neutralization of acidity and increase in pH.

A decrease in pH of alkali or calcareous soils is the result of accumulation of carbon dioxide in flooded soil, which neutralizes alkalinity. Moreover, carbon dioxide produced is retained in the flooded soil due to restricted diffusion through standing flood-water layer on the soil surface. This allows large quantities of carbon dioxide to accumulate and form mild acid, which help in neutralizing alkalinity in the soil–floodwater system (see eqs (2) and (3)). Moreover, submerged soil provides an ideal environment for reaction between carbon dioxide-generated acid (carbonic acid) and alkalinity.

$$CO_2 + H_2O = H_2CO_3. \quad (2)$$

$$H_2CO_3 = H^+ + HCO_3^-. \quad (3)$$

Ponnamperuma *et al.*[14] studied the influence of redox potential and partial pressure of carbon dioxide on the pH values of 35 diverse rice soils (pH range between 3.6 and 9.4) from the Philippines, Taiwan and Vietnam. The soils were held in flooded condition in pots in the greenhouse and changes in soil solution pH, redox potential and partial pressure of carbon dioxide were monitored for 16 weeks. The results showed that the pH values of alkali and calcareous soils decreased and those of acid soils increased to a fairly stable range of 6.7 to 7.2, 12 weeks after flooding. Further, it was established that the increase in soil solution pH of the acid soils was related to the potential of the Fe $(OH)_3$–Fe (II) system and that the decrease in pH of alkali and calcareous soils was defined by the partial pressure of carbon dioxide through the Na_2CO_3–H_2O–CO_2 and $CaCO_3$–H_2O–CO_2 systems respectively. The pH values were sensitive to carbon dioxide changes in the soil solution.

Thus accumulation of large amounts of carbon dioxide in submerged soils acts an ameliorating agent by neutralizing the alkalinity. Adding organic carbonaceous materials, which would generate extra carbon dioxide on decomposition, can enhance the generation of carbon dioxide, especially in soils low in organic matter. However, if the carbon dioxide produced is allowed to escape from the soil–water system, it would result in increasing the pH of the soil–water system.

Thus iron reduction and carbon dioxide concentration in submerged soils play a key role in controlling the pH of submerged soils. This, of course, requires optimum temperature (between 25 and 35°C) and availability of easily decomposable organic matter, reducible iron and other electron acceptors such as sulphate and carbon dioxide[8,15].

Narteh and Sahrawat[13] studied the influence of flooding on the changes in electrochemical and chemical properties of 15 diverse soils from West Africa by monitoring the changes in soil solution drawn periodically from soils held under flooded condition in pots in the greenhouse. They found that at four weeks after flooding of soils, the pH of the soil solution could be predicted from the soil solution redox potential (Eh in mV) and the concentration (mg l^{-1}) of Fe (II) in soil solution by the following equation:

$$\text{Eh} = 409–4.09 \log\text{Fe}^{2+}–59 \text{ pH}; R^2 = 0.99. \quad (4)$$

It was further demonstrated that the changes in soil solution pH corresponded to the changes in soil solution Eh. A dynamic stability in Eh–pH relationship was established at four weeks after flooding of the soils and was described by the following equation:

$$\Delta\text{Eh} = –16–48 \Delta\text{pH}; R^2 = 0.84. \quad (5)$$

Considering all the 15 soils at four weeks after flooding, the soil solution electrical conductivity (EC) (mScm^{-1}) was significantly correlated with the concentrations of Ca, Mg, K and ammonium (Table 3). Also, at four weeks after flooding, the mean EC value of the soil solution was highly significantly correlated with the mean total concentration of Ca, Mg and K in the soil solution ($r = 0.91$)[13]. Ponnamperuma[16] reported similar results on the relationship between soil solution EC and solution concentration of basic cations in flooded Asian soils.

Sahrawat and Narteh[17] showed that at four weeks after flooding of the 15 West African soils, the soil solution EC was highly significantly correlated with the total concentration of macro- and micronutrient elements released in the soil solution.

Solution EC (mS cm^{-1}) = –0.191 + 0.0055 nutrient conc. in solution (mg l^{-1});

$$r = 0.927 \ (n = 15). \quad (6)$$

This four-week period coincided with the establishment of a dynamic equilibrium between pH and Eh. The soils had a wide range in solution EC, indicating a range in soil fertility status. The soil solution EC was significantly correlated to organic C and iron extracted by EDTA. The association bet ween soil solution EC, concentrations of macro- and micronutrient elements in soil solution, organic C and EDTA-extractable iron of the soils is seen[17] in Table 4. It is suggested that the soil solution EC at four weeks after flooding of the soils can serve as an index of fertility status of soils that are not affected by salts[17].

Table 3. Correlation between soil solution EC of 15 flooded West African soils and concentration of important nutrient elements in soil solution at four weeks after flooding. Probability levels of significance (*P*) are shown in parentheses[13]

Nutrient element	Correlation coefficient (r)
K	0.85 ($P < 0.001$)
Ca	0.86 ($P < 0.001$)
Mg	0.84 ($P < 0.001$)
Total K + Ca + Mg	0.91 ($P < 0.001$)
Ammonium-N	0.62 ($P < 0.001$)

The availability of free water on the soil surface not only relieves moisture stress, but also provides a more conducive environment to rice roots, and availability and accessibility of nutrients through diffusion and mass flow to plant roots[9]. The convergence of soil pH to neutrality following submerging of soils benefits wetland rice crop through better availability of nutrients such as ammonium, P, K and exchangeable cations, which are mobilized in soil solution. It has been shown that preflooding of soil for about four weeks prior to transplanting of the rice seedlings, leads to the release of ammonium, phosphate, K and other exchangeable cations in the soil solution, which is good for the growth of rice plants. This may allow rice farmers to skip the basal application of nitrogen fertilizer in some cases. The extent and release of ammonium and other cations and anions will depend on soil chemical characteristics including pH, organic matter and texture[8,9,13,18].

From this discussion, it can be concluded that flooding soil is a great equalizer of diversity in chemical fertility of wetland soils. This change is brought about by consumption of acidity in acid soils and the neutralization of alkalinity in alkaline and calcareous soils following flooding. As a result of flooding, the pH of acidic soils increases and that of alkaline soils decreases and the chemical reaction of submerged soils generally stabilizes in the neutral range[8,13]. This is the benefit of flooding of soils to rice crop.

The convergence of pH to near neutral also affects the availability of plant nutrients mostly in a favourable manner. However, soil reduction, following flooding of soils that are rich in reducible iron, accumulates excessive concentrations of iron in the soil solution that could be toxic to wetland rice. Also, production of reduction products in submerged soils, such as sulphide and organic acids in flooded soils, may cause toxicity and retardation of rice plant growth, especially in soils that are high in easily decomposable organic matter or if high amounts of organic materials are added to the soil[9]. Salient changes in the availability of plant nutrients and organic matter accumulation as a result of flooding of soils, gleaned from the literature, are summarized in Table 5.

Submerging soil and organic matter accumulation

The decomposition of soil or added organic matter is relatively fast under aerobic conditions where oxygen is the electron acceptor. However, under submerged conditions the supply of free oxygen is low or absent and the decomposition of organic matter depends on the availability of electron acceptors such as ferric iron or sulphate. Moreover, the alternate electron-acceptors (ferric hydroxides or sulphate) are inefficient in the destruction of organic matter compared to oxygen. Consequently, the decomposition of organic matter is comparatively slow, inefficient and incomplete under flooded or anaerobic soil conditions. Coupled with retarded rates of organic matter decomposition in submerged soils, the higher primary productivity of wetlands, contribution by

Table 4. Distribution of 15 West African soils according to the concentration of macro- and micronutrient elements in soil solution at four weeks after flooding, and the associated soil solution EC, organic C and EDTA extractable iron (EDTA–Fe)[17]

Conc. of nutrients in solution (mg l^{-1})	Soil solution EC (mS cm^{-1})	No. of soils	Organic C (g kg^{-1})	EDTA–Fe (mg kg^{-1})
> 200	0.72–1.92	3	23.0–46.0	150–2200
100–200	0.25–0.92	8	7.4–35.2	125–1375
< 100	0.12–0.30	4	9.2–23.2	450–800

Table 5. Changes in organic matter and availability of plant nutrients in soils following their submergence under water

Chemical property	Change(s) following soil submergence
pH	Favours convergence to neutral pH
Organic matter	Favours accumulation of organic C and N
Ammonium-N	Release and accumulation of ammonium favoured
P	Improves P availability, especially in soils high in Fe and Al oxides
K	K availability improves through exchange of K
Ca, Mg, Na	Favours release of Ca, Mg and Na in solution
S	Sulphate reduction may reduce sulphur availability
Fe	Iron availability improves in alkali and calcareous soils, but Fe toxicity may occur in acidic soils high in reducible Fe
Al	Al toxicity is generally absent, except perhaps in acid sulphate soils
Cu, Zn and Mo	Improves availability of Cu and Mo but not of Zn
Reduction products	Production of sulphide and organic acids, especially in degraded soils may cause toxicity or injurious effects to growing plants

biological nitrogen fixation and decreased humification of organic matter lead to preferential (compared to aerobic counterpart soils) accumulation of organic matter in wetland soils and sediments[6].

Sahrawat[6] cites several examples from recent literature, which show that accumulation of organic C and N in submerged soils is significant in wetland rice double-cropping, even during short-term experiments. The use of an upland crop in the crop sequence with wetland rice resulted in decreased organic C and total N.

Relatively higher accumulation of organic matter (organic C and total N) in wetland soils makes them attractive for sequestration of C for increasing the fertility of wetland soils and at the same time mitigating greenhouse emissions[19]. Unlike in aerobic soils, such effects can be significant during relatively short periods. For example, Witt *et al.*[20] conducted a two-year experiment under irrigated condition to study the effects of crop rotation and residue management on C sequestration and N accumulation, and rice productivity. They found that compared to the rice–rice system replacement of dry-season rice by maize caused a reduction in soil C and N sequestration due to a 33–41% increase in the estimated amount of mineralized C and less input from biological N fixation during the dry-season maize crop. There was 11–20% more C sequestration and 5–12% more N accumulation in soils continuously cropped with wetland rice, than in maize–rice rotation with greater amounts sequestered in N-fertilized treatments. These results demonstrate the capacity of continuous, irrigated rice systems to sequester C and accumulate N during relatively short time-periods.

Application of crop residues such as rice straw, has a beneficial effect on the build-up of organic matter and in increasing the N-supplying capacity of wetland rice soils. This is due to the fact that there is a strong relationship between organic matter content and potentially mineralizable N[21]. Moreover, application of organic matter to submerged soil provides energy for soil changes in pH and Eh, thus resulting in benefits in terms of nutrient release and availability to wetland rice[12]. Thus flooding soil through accumulation of organic matter (organic C and N) imparts stability and sustainability in crop productivity and maintenance of fertility in wetland soils.

Perspectives

Flooding a soil with water sets in motion a series of physical, chemical and biological processes. Changes in flooded soils are triggered by lack of oxygen in the flooded soil-system. The soil gets reduced (lower Eh; see Tables 1 and 2), for which energy is provided by mineralizable organic C. The reduction process is regulated by the presence and availability of electron acceptors (mainly ferric iron and sulphate) and electron donors (organic matter). Soil reduction is accompanied by changes in the pH, Eh, specific conductance, sorption–desorption, ion exchange and exchange equilibria, which in turn greatly influence the availability of plant nutrients, uptake and utilization by wetland rice[9].

Soils with moderate to high content of organic matter or added organic matter can help adjust soil pH to the neutral range (6.5–7.5), which is of benefit to the rice crop, because this pH range appears to favour nutrient uptake by wetland rice. Availability of N (ammonium is stable in reduced soils), P, K, Ca, Mg, Fe, Mn and Si is high (see Table 5). The supply of micronutrients such as Cu and Mo is adequate[22]. Generally, the availability of Zn is reduced as result of submergence of the soil[23]. Toxic concentrations of Al and Mn in soil solution are absent in submerged mineral rice soils, because the solubility of these metals is reduced as a result of increase in soil pH[8]. However, Fe toxicity and injurious concentrations of organic acids and sulphide may be present to cause toxicity to lowland rice, especially in soils with high organic matter and impeded drainage[23].

The rice–wheat system occupies 24 mha of cultivated land in the Indo-Gangetic Plains and in China, and is one the world's largest production system. Recent results from long-term experiments indicate that soil organic matter levels have declined[24,25]. Several hypotheses have been put forth to explain the declining trend in organic matter content and accompanying decline in yields, including lack of application of organic matter input and decreased nutrient supplying capacity of the soil, especially N. However, results from long-term experiments with the rice–rice (lowland) system show that organic matter is generally maintained or even increased[6]. Clearly, organic matter accumulates under submerged conditions of the rice–rice system. On the other hand, organic matter that accumulates under lowland rice is rapidly oxidized under arable cropping of wheat in the rice–wheat rotation production[6].

Higher net primary productivity has been ascribed as the important factor for increased organic matter in tropical wetlands[26]. Flooded soil provides an ideal environment for aerobic and anaerobic microbial activity in its floodwater and contributes to higher net primary productivity[27]. Wetlands are important for sequestering carbon from the atmosphere under anaerobic metabolism. Protection of existing wetlands and creation and restoration of new wetlands will contribute to carbon sequestration for mitigating greenhouse emissions[19,28,29].

Wetland rice culture favours fertility maintenance and build-up of organic matter in soils, and is the backbone of long-term sustainability of the wetland rice systems[6]. Further strategic research is needed in the field and through the use of simulation modelling for studying and evaluating the comparative effects of growing rice under submerged condition in rice paddies and under various alternate water-management practices that save and conserve water on soil fertility maintenance in the longer-term. Such research would help in making an appropriate decision by considering trade-offs between water-saving and yields, and fertility maintenance for the future growing of an important staple such as rice.

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