Soil Organic Matter Persistence and Mineral Association Under Flooded and Aerobic Cultivation of Oryza sativa

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Abstract

Background: Paddy soils used to cultivate Oryza sativa (rice) cover about 155 million hectares around the world, providing a vital link between agricultural production and sustainable environmental systems. In rice-based systems, soil organic matter (SOM) dynamics are regulated by a multitude of complex interactions involving hydrologic (water-related), mineralogical, microbial (bacterial) activity and plant inputs. Flooded (anaerobic) versus aerobic cultivation creates an opposite combination of redox (chemical oxidation-reduction) conditions that dramatically change SOM transformation pathways, organo-mineral dynamic interactions and GHG emissions.

Objective: This review offers a detailed examination of the mechanisms that are responsible for the long-term maintenance of SOM and its relationship to minerals in flooded and aerobic rice cultivation systems, with emphasis on the interactions between SOM and mineral materials primarily related to the presence of Fe/Al oxides and clay minerals, the role of microbial necromass, and the implications of various water management strategies such as AWD, which alter the biogeochemical processes within these environments.

Methods: We conducted an organized assessment of articles published within the peer-reviewed academic literature from 2010 through 2025. The integration used literature related to 3 types of methods that have been used in the soil fractionation process (i.e., density, particle size, and chemical), isotopic tracing (i.e., 13C and 15N), spectroscopic methods (i.e., NMR, FTIR, and XPS) and tools to study microbiological communities (i.e., metagenomics and enzyme activities) and the synthesis of comparative data with long-term (10+ years) field studies across rice (Oryza sativa) producing countries.

Results: Flooding greatly increases the amount of SOM (soil organic matter) by reducing oxidative breakdown (decomposition) processes, reducing Fe oxide solubility which releases OC (organic carbon) that was previously bound, and increasing the accumulation of microbial carcasses. Mineral-associated OC (MAOC) comprise 60% to 75% of the total OC found in flooded paddy soils primarily bound to amorphous Fe phases. Aerobic systems usually have faster SOM turnover compared to anaerobic systems but also provide higher aggregate stability, enhanced nitrogen mineralization and greater oxidative enzyme activity. Alternate Wetting-Drying (AWD) is an effective management tool for accomplishing both the reduction of CH4 (methane) emissions by 30-50%, while having little to no impact on SOM stocks. However, it is possible that N2O (nitrous oxide) emissions could be increased as a result of using AWD methods.

Conclusion: The dynamic balance between microbial interactivity with soil organic matter, mineral stabilization of organic matter and redox-driven transformations determines the persistence of soil organic matter (SOM) in paddy soils. Integrated management of organic additions, optimized hydrology and site-specific mineral conditions will result in effective carbon sequestration of SOC in paddy agroecosystems. Future research will focus on determining the long-term stability of MAOM under changing climate-induced hydrology and quantifying the contribution of MAOM from microbial necromass to long-lived SOC pools.

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Keywords: Oryza sativa, soil organic matter, organo-mineral associations, flooded cultivation, aerobic rice, redox dynamics, carbon sequestration, alternate wetting and drying, methane emissions, microbial necromass

1. Introduction

Rice is the staple food for over half of the world's population (Oryza sativa L). Most rice is produced in flooded paddies. Because flooded paddy soils are subject to alternating oxidising and reducing conditions, they are important regulators of how soil organic matter (SOM) is transformed, stabilised, and lost (Neue *et al*. 1990) [1] (Sahrawat 2004) [2]. The hydrological management of rice paddies affects rice yield, but it also affects the carbon sequestration potential of rice paddies, nutrient cycling efficiency, and the emission rates of climate active trace gases (e.g. CH_4, CO_2, N_2O), all of which are influenced by how rice paddies are managed (Pan *et al*. 2010) [3].

SOM refers to soil organic matter, which is the primary element for maintaining soil fertility, as well as for maintaining healthy ecosystems. There are several mechanisms that contribute to the long-term stability of SOM, and they come from many different interacting factors, including 1) the chemical obstinacy of SOM (recalcitrance), 2) the physical protection of SOM when present in soil aggregates and 3) the mineral-organic interactions that limit microbial access to organic substrates in the soil (Schmidt *et al*., 2011) [4] (Lehmann and Kleber, 2015) [5]. In rice (Oryza sativa) agroecosystems, the stabilization mechanisms that control SOM are also influenced by: 1) variations in the redox potential of the soil and 2) the physiological structure of the plant's roots and its ability to take up nutrients and immobilize CO2, and 3) the mineral content of the tropical and subtropical soils in which rice is grown (Kuzyakov and Xu, 2013) [6] (Wissing *et al*., 2011) [7].

Flooded rice systems to Dry or Aerobic Rice Systems transition is based entirely on concern for water scarcity and would also improve the opportunity to increase production in a sustainable fashion. The transformation of these two systems will result in a soil biogeochemical environment that is very different than that found in continuously flooded paddies which have undergone highly reduced redox potentials (Eh < -200 mV), vs. aerobic systems which occur with positive soil redox potentials (Eh > +300 mV). Thus, our ability to develop an effective water management strategy that optimizes both productivity and environmental stewardship will be reliant upon understanding how such differing redox environments will affect the dynamics of SOM and its formation from mineral substrates.

The stabilization of Soil Organic Matter (SOM) is strongly based on organo-mineral association, specifically organo-mineral associations that include Fe, Al and clay minerals. With continuous flooding, the enhanced reduction and oxidation of Fe minerals through changes in redox potential create a cycle of dissolution and reprecipitation, which impacts the availability of sediments to act as a substrate for organic matter. Under aerobic conditions, mineral feedstocks containing Fe3 and Al3 oxide crystals and high specific surface areas provide bonding sites for organo-mineral bonding through ligand exchange, electrostatic forces and hydrophobicity.

It is the intent of this broad review of literature to compile the existing knowledge of SOM dynamics, its persistence mechanisms, and its association with minerals in rice cultivated in both flooded and non-flooded systems. This literature will be compiled using molecular spectroscopy, isotopic field studies and agronomic field trials over the long term to arrive at a mechanistic basis for the stabilization of carbon within rice systems using multiple methodologies. The forces of this compilation will emphasize the implications of this body of literature with regard to climate smart agricultural practices and the establishment of sustainable rice production policy.

Table 1: Comparative physicochemical properties of paddy soils under flooded and aerobic Oryza sativa cultivation systems across major rice-producing regions.

Property	Flooded (Anaerobic)	Aerobic	Reference
Redox potential (Eh, mV)	−200 to −300	+200 to +400	[9, 15]
Soil pH	6.5–7.0 (buffered)	5.0–6.5 (variable)	[16]
Dissolved O_2 ($mg\ L^{-1}$)	<0.5 (hypoxic)	5–9 (near-saturation)	[9]
Organic carbon ($g\ kg^{-1}$)	15–35 (accumulation)	8–20 (turnover)	[3, 17]
Fe^{2+} ($mmol\ kg^{-1}$)	50–200 (elevated)	<5 (oxidized)	[11]
NH_4^+-N ($mg\ kg^{-1}$)	50–150 (dominant)	10–30 (limited)	[18]
NO_3^--N ($mg\ kg^{-1}$)	<2 (depleted)	20–80 (elevated)	[18]
Microbial biomass C ($mg\ kg^{-1}$)	200–600	350–900	[19]
CH_4 flux ($kg\ ha^{-1}\ season^{-1}$)	80–400	<5	[20]
Aggregate stability (MWD, mm)	1.2–2.0 (moderate)	2.5–4.5 (high)	[21]

2. Soil Organic Matter Dynamics in Rice-Based Systems

2.1. Composition and Fractionation of SOM in Paddy Soils

Based on their likelihood to degrade chemically or biologically, there are two different types of soil organic matter pools within the rice agroecosystem: labile and recalcitrant (Christensen, 2001) [22]. The labile pool consists of light fraction organic matter (LFOM) and dissolved organic carbon (DOC), which have a rapid turnover rate (months to years) and high biological reactivity. In contrast, the recalcitrant pool contains various materials such as humin, black carbon, and MAOM which can persist for centuries to thousands of years, establishing the recalcitrant pool as the predominant long-term carbon reservoir within soils (Schmidt *et al*., 2011) [4] (Golchin *et al*., 1994) [23].

Flooded rice systems have a large variance between labile and recalcitrant soil carbon (%) when compared to the ratios found in well-drained agricultural systems. Prolonged water saturation alters the aerobic respiration process in soils causing organic (litter, residues) to undergo incomplete oxidation when decomposing. In addition to this, partially oxidized amounts of organic matter are being stored in solid (soil) and liquid (water) phases (Reddy and Patrick 1984) [24]. Density fractionation studies reveal that the percentage of the total amount of organic carbon in flooded rice soils, heavily fractionated with respect to mineral-association (occupying 60-75% of the total), is higher than in well-drained rice soils (occupying 45-60% of the total)(Lehmann and Kleber 2015) [5] (Wissing *et al*. 2014) [25].

Nuclear magnetic resonance (NMR) spectroscopy has been used to examine paddy soil humic materials. The results indicate that O-alkyl carbon (representative of sugars and/or cellulose) is present in greater amounts in flooded (anaerobic) systems compared to aerobic soils, which contain primarily aromatic and alkyl carbon (due to preferential retention in O2-oxidizing conditions) (Olk *et al*., 2006) [26]. Differences in composition of the SOM affect their resilience to variations in water management.

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Table 3: Soil organic matter fractions and their characteristics in flooded versus aerobic paddy soils under Oryza sativa cultivation.

SOM Fraction	Method	Flooded (% of SOC)	Aerobic (% of SOC)	Turnover Time
Light fraction OM (LF)	Density (<1.8 g cm^{-3})	15–25	20–35	Months–years
Heavy fraction OM (HF)	Density (>1.8 g cm^{-3})	60–75	45–60	Decades–centuries
Particulate OM (POM)	Size (>53 µm)	20–30	25–40	Years
Mineral-assoc. OM (MAOM)	Size (<53 µm)	55–70	40–55	Centuries–millennia
Dissolved OC (DOC)	0.45 µm filtrate	3–8	2–5	Days–weeks
Microbial biomass C (MBC)	Fumigation extraction	2–5	3–7	Weeks–months
Humic acids (HA)	NaOH extraction	10–20	15–25	Decades
Fulvic acids (FA)	NaOH extraction	8–15	10–18	Years–decades
Labile C ($KMnO_4$-oxidizable)	Chemical oxidation	5–12	8–18	Months
Recalcitrant C (non-hydrolyz.)	Acid hydrolysis	20–35	15–28	Centuries

2.2. Sources of SOM in Paddy Soils

Organic materials that are used in paddy soils originate from three main sources: 1) crop residues left on the surface after harvesting (straw), 2) roots and root exudates from below-ground that die naturally, and 3) the mass of bacteria and fungi that develop in soils once the residues and bodies of roots have been removed (Liang *et al*., 2019) [47]; (Miltner *et al*., 2012) [53]. Compost and other forms of organic matter can supplement the organic matter already present in paddy soils (Lu *et al*., 2009) [28]. The manner in which crop residues are managed has a substantial influence on total organic carbon (OC) stock and its distribution with regard to lability, as a result of incorporation/removal of crop residues (Lu *et al*., 2009) [28]. The amount of carbon that can be incorporated into soils through rice straw (approximately 30 to 50 kg C mg^{-1} of straw) depends heavily on soil redox conditions (Sander *et al*., 2014) [21]; (Yan *et al*., 2005) [20]. Root-derived organic carbon (OC), from the turnover of root biomass, low molecular weight organic acids, sugars, amino acids, and mucilage from rhizodeposition, constitutes an important portion (~20-40%) of the total OC of paddy soils providing both an input of total OC via root systems (root systems) and a source of organic material for the total OC of paddy soils via microbial decomposition of root-derived materials (Jones *et al*. 2009) (Aulakh *et al*. 2001). The release of oxygen through aerenchymal tissue of Oryza sativa (rice) creates a uniquely oxidizing microsite (rhizosphere oxidation zone) adjacent to an anaerobic (bulk) soil matrix creating steep (i.e. rapid) chemical gradients and thus promoting rapid (and) organo-mineral formation (Colmer 2003) (Weiss *et al*. 2003). Additionally, OC from root-derived materials are also major contributors to paddy soils through aerobic (non-anoxic) management systems; however they are much more susceptible to rapid microbial decomposition resulting in lower net accumulation of OC compared to paddy soils (Kuzyakov 2010; Zhang *et al*. 2018) (Kuzyakov 2010; Zhang *et al*. 2018).

2.3. Rhizosphere Processes and SOM Turnover

The biogeochemical processes that are occurring in the O. sativa (rice) rhizosphere occur within regions that are generally larger than those found within the surrounding bulk soil, exhibit higher levels of microbial biomass and higher levels of microbial activity than is found within surrounding bulk soil (Breidenbach, 2016) [48]. Soil microorganisms are supported by the availability of carbon (C) in different forms through the exudation of carbon from rice roots and this can lead to accelerated rates of decomposition of native soil organic matter (SOM) through the process known as rhizosphere priming effects (RPE) (Kuzyakov, 2010) [27] & Jones *et al*., 2009) [29] as well as the direction of the RPE has been shown to be influenced by soil redox status (Zhu *et al*., 2018) [31]. Under anaerobic conditions (i.e., under flooding), the absence or limited activity of oxidative enzymes (ligninases and cellulases) consequently limits soil microorganisms ability to efficiently access recalcitrant substrates and therefore limits the total loss of soil organic matter from soil due to the high levels of rhizodeposition associated with rice production (Freeman *et al*., 2001) [32] & Sinsabaugh, 2010) [43].

Anaerobic soils can create edified areas in the soil where some zones have been oxidized due to oxygen being released from the rice roots, called radial oxygen loss (ROL) (Colmer, 2003) [30]. In these oxidized areas of soil, iron deposits form on the rice root (iron oxyhydroxide coatings)—again due to ROL from the rice root (Liu *et al*., 2004) [33] (Weiss *et al*., 2003) [34]. These iron deposits have a very high specific surface area (50 - 150 $m^2 g^{-1}$), making them a great candidate to support the adsorption of organic carbon (OC) on the surface of the iron deposits. Organic carbon can become adsorbed on those iron deposits or iron plaques for two primary reasons: resulting from adsorption of dissolved organic C (low molecular weight) and dissolved organic acids and amino acids (Kaiser and Guggenberger, 2000) [42].

The formation and breakdown of rhizosphere iron plaques create an opportunity for the dynamic exchange of OC between the solid and liquid phases within the rhizosphere, over both daily and seasonal time intervals (Riedel *et al*., 2013) [12].

2.4. Differences in SOM Inputs Under Flooded vs. Aerobic Cultivation

Total SOC stocks are higher (20-50%) in continuously flooded paddies compared to aerobic paddies, due to lower decomposition rates, more biomass allocated below ground, and the accumulation of organic matter that has been partially reduced (Wissing *et al*., 2014) [25] (Sahrawat, 2004) [2]. While aerobic agriculture supports higher microbial biomass from increased O2 supply, they also result in faster SOM mineralization and lower SOC stocks (Kögel-Knabner *et al*., 2010) [15]. However, aerobic systems promote the formation of stable macroaggregates that physically protect occluded POM from microbial degradation but do not completely offset the effects of higher decomposition on SOC stocks (Six *et al*., 2002) [51] (Golchin *et al*., 1994) [23].

The compared SOM inputs into soil vary between flooded and aerobic rice farming. Flooded soils conserve labile compounds (simple carbohydrates, amino acids) because anaerobic processes inhibit oxidative catabolism, whereas aerobic soils use more oxidative catabolism to process labile compounds, which results in more selective accumulation of alkyl carbon structures that are resistant to further oxidative destruction (Olk *et al*., 2006) [26] (Conrad, 2009) [38]. This difference in SOM quality creates implications for nutrients from soil and long-term carbon storage.

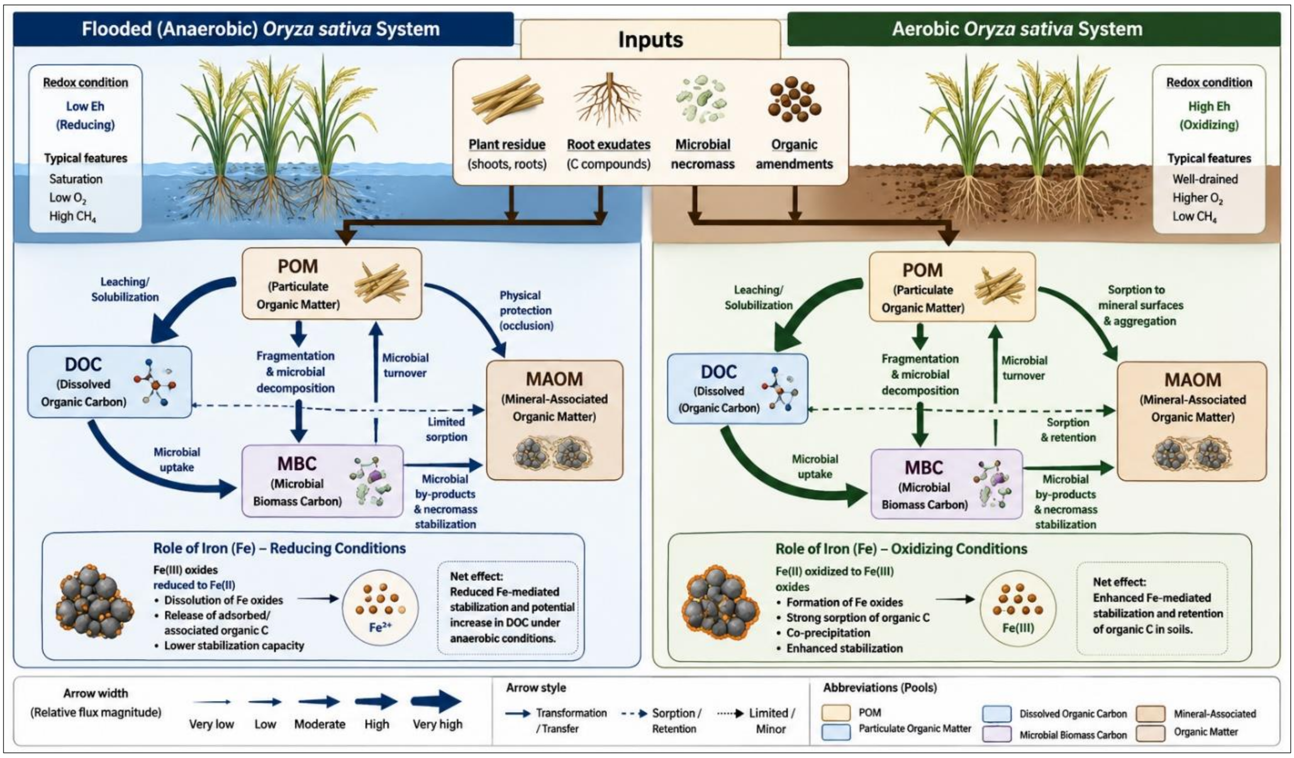


Fig 1: Soil organic matter transformation and stabilization pathways in flooded and aerobic *Oryza sativa* systems

3. Biogeochemical Processes Under Flooded and Aerobic Conditions

3.1. Redox Potential Dynamics and Oxygen Availability

The hydrological characteristics of paddy soils identify the sequence of terminal electron accepting processes (TEAP's) that determine the rate and extent at which soil organic matter (SOM) decomposes, nutrients transform, and minerals weather (Reddy and DeLaune, 2008) [9] (Nealson and Stahl, 1997) [37]. When soils become flooded, the dissolved oxygen (O_2) that is in the soils rapidly will be consumed by aerobic heterotrophic organisms within approximately 24 to 48 hours after flooding which will result in sequential use of alternative electron acceptors in thermodynamic order: nitrate (NO_3^-) reduction (Eh +200 to +400 mV), manganese (Mn^{4+}) reduction (+400 to +200 mV), iron (Fe^{3+}) reduction (−100 to +100 mV), sulfate (SO_4^{2-}) reduction (−150 to −200 mV), and lastly methanogenesis (<−200 mV) (Conrad, 2009) [38] (Lovley and Goodwin, 1988) [39].

There are significant differences in the timing and amount of redox potential in flooded paddy soils due to root fungal (mycorrhizae) oxygen release, organic matter hotspots (areas where organic matter has accumulated), and macropore (large, continuous and interconnected air spaces) flow (Colmer, 2003) [30]. The redox potential in flooded paddy soils becomes relatively stable (Eh values between −200 and −300 mV) in the bulk soil within 2 to 4 weeks of being submerged. However, the rhizosphere surrounding the aerobic rice plant maintains small zones of elevated redox potential (Eh between +100 and +200 mV) even during flooding (Weiss *et al*., 2003) [34]. This microscale heterogeneity of redox potential is an important factor, which contributes to the localized dynamics of the interaction between organics and minerals in soil.

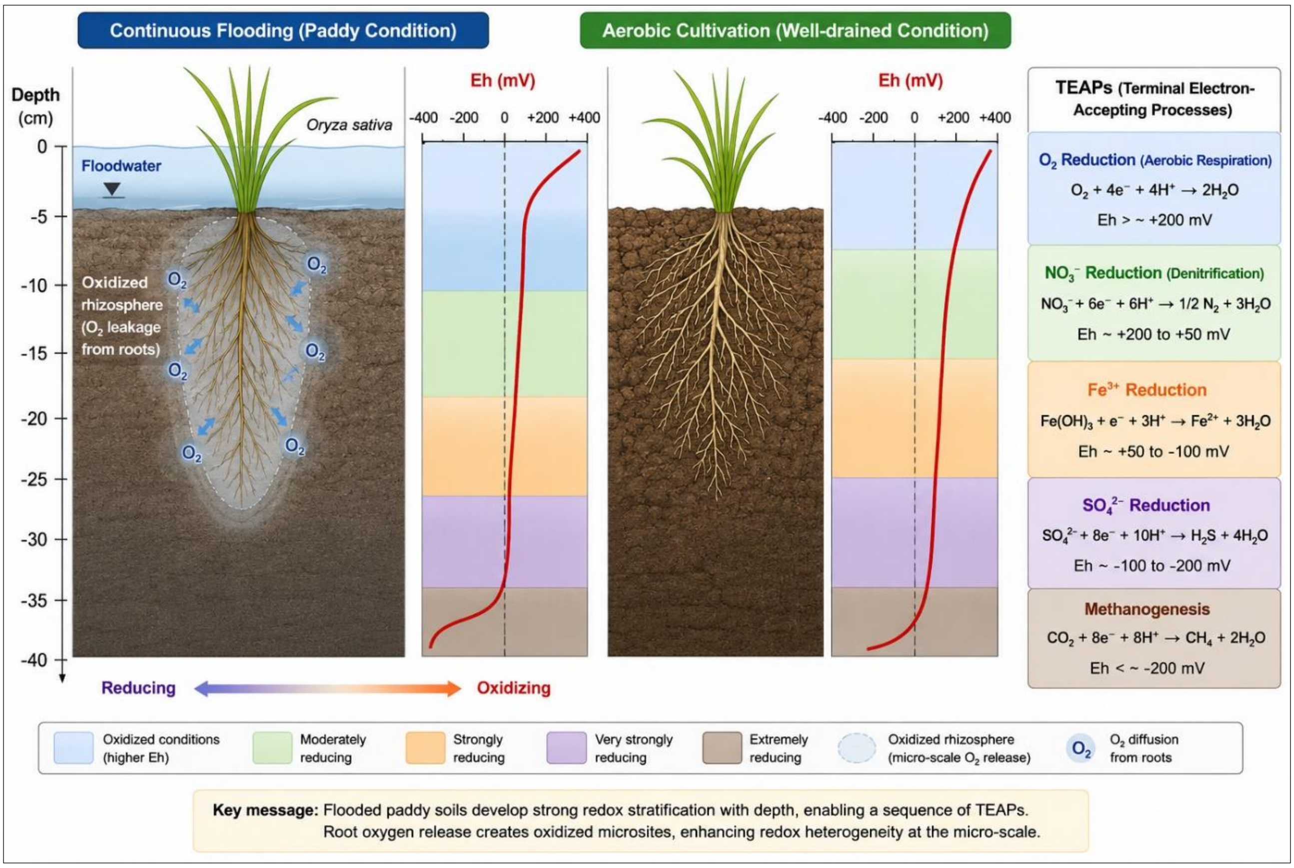


Fig 2: Redox Potential (Eh) Gradients in Paddy Soils Under Continuous Flooding and Aerobic Cultivation

3.2. Anaerobic Decomposition Pathways

The predominant organic matter decomposition pathways move from aerobic respiration under inundated situations to anaerobic processes such as fermentation, dissimilatory iron-reducing bacteria, and methanogenesis (Conrad, 2009) [38] (Lovley and Goodwin, 1988) [39]. The inefficiency of anaerobic processes compared to their aerobic counterparts results in fermentation intermediates like acetate, propionate, butyrate, and hydrogen that will continue to build up as by-products of the decaying organic materials until they can be utilized (as a substrate) for sulfate-reducing bacteria and methanogenic archaea during the final stages of anaerobic decomposition (Yao *et al*., 1999) [40] (Conrad, 2009) [38]. Dissimilatory iron reduction (DIR), catalyzed by iron-reducing bacteria (FeRB), such as Geobacter and Shewanella spp., plays a dual role in soil and organic matter-related processes (Weber *et al*., 2006) [41]. While these microorganisms oxidize organic matter with ferric iron (Fe^{3+}) as the electron acceptor, the reduction of ferric minerals to soluble ferrous iron (Fe^{2+}) also enhances the release of organic carbon that was associated with iron into solution or back into solution (Riedel *et al*., 2013) [12] (Kaiser and Guggenberger, 2000) [42]. This mobilization of SOm-associated organic carbon represents a potentially significant but currently underappreciated pathway of carbon loss in flooded paddy soils (approximately 5–20% of the organic carbon pool annually from highly reduced soils) (Fimmen *et al*., 2008) [11] (Weber *et al*., 2006) [41].

3.3. Aerobic Mineralization and Oxidative Enzyme Activity

The pervious sentence demonstrates that using aerobic processes, namely bacteria that utilize O2 for respiration, can improve the breakdown of organic matter using a range of aerobic heterotrophic microorganisms through the enzymes they produce that oxidize organic matter, such as laccase, peroxidase, cellulase, and proteolytic enzymes. The combination of these enzymes can attack complex molecules made from lignin, cellulose, and hemicellulose, lay dormant until drainage or flooding occurs, and eventually build up in the soil (Sinsabaugh *et al*., 2009) [44], and there has been considerable scientific interest in these enzymes and their respective laccase and peroxidase activities (compared to that of flooded paddy soils) since they represent a means for determining the oxidative processes that occur in soils during anaerobic or flooded conditions.

Consequently, as a result of the significantly higher levels of demonstrable enzyme activity in aerobic soils compared to flooded soils, the rate of organic carbon mineralization is considerably accelerated, resulting in noticeably greater rates of CO_2 efflux and lower net soil organic carbon accumulation in aerobic rice production systems compared to flooded rice paddy systems when overall seasonal differences are used as the basis for determining these relative effects (typically two to five times greater in the aerobic systems) (Inubushi *et al*., 2003) [46].

In addition to this substantial difference in the total quantities of CO_2 effluxed from the aerobic rice production system, aerobic soil conditions also foster the generation of a multitude of different types of stable microbial metabolites, such as melanin, glycoproteins, cell wall polysaccharides, and other compounds that contribute greatly to the formation of the recalcitrant soil organic matter pool (Lehmann and Kleber, 2015) [5] (Liang *et al*., 2019) [47] as a result of the microbial carbon pump effect.

3.4. Microbial Communities in Carbon and Nitrogen Cycling

Hydrology is the primary influencing factor on the microbial community composition in paddy soils as shown by numerous metagenomic studies showing that flooded paddy soils are dominated by anaerobic guilds such as methanogen (Methanosarcina and Methanobacterium), iron-reducing bacteria, and fermenters, while aerobic systems are characterised by aerobic decomposers, nitrifiers and denitrifiers (Zhang *et al*., 2018) [19] (Breidenbach *et al*., 2016) [48]. The redox conditions of flooded vs. aerobic soils are especially relevant when considering nitrogen cycling, as flooding promotes ammonification and impedes nitrification due to O_2 limitation, resulting in the accumulation of NH_4^+ as the main source of mineral nitrogen (Sahrawat, 2010) [18]. Conversely, aerobic soils support active nitrification/denitrification coupled cycles because of the available oxygen, leading to higher concentrations of NO_3^- and increased potential for N_2O emissions (Aulakh *et al*., 2001) [49]. Therefore, the diversity and activity of N-cycling microbial communities are important determinants of nutrient use efficiency in rice production systems.

Table 4: Microbial community characteristics and enzymatic activities in flooded versus aerobic paddy soils under Oryza sativa cultivation.

Parameter	Flooded System	Aerobic System	Method	Reference
Dominant functional groups	Methanogens, FeRB, fermenters	Aerobic heterotrophs, nitrifiers	16S rRNA metagenomics	[19, 48]
Microbial diversity (Shannon H)	3.8–5.2 (moderate)	4.5–6.1 (high)	Amplicon sequencing	[48]
Cellulase activity (nmol h^{-1} g^{-1})	15–45 (suppressed)	60–180 (active)	Substrate assay	[44]
Phenol oxidase (nmol h^{-1} g^{-1})	2–8 (very low)	25–90 (high)	Colorimetric assay	[45]
β-glucosidase (nmol h^{-1} g^{-1})	20–60	50–140	pNP assay	[44]
N-acetyl-glucosaminidase	10–30	30–80	pNP assay	[44]
Denitrification rate (µg N kg^{-1} d^{-1})	80–250 (high)	15–60 (moderate)	Acetylene inhibition	[49]
Methanogen abundance (copies g^{-1})	10^7–10^9 (high)	$<10^4$ (negligible)	qPCR mcrA gene	[48]

4. Mechanisms of Soil Organic Matter Persistence

4.1. Chemical Recalcitrance versus Physical Protection

The evolution of our understanding of SOM stability has been shaped primarily by the principles of chemical resilience – the theory that chemically complex compounds such as lignin, tannins and suberin are resistant to breakdown by microorganisms because of their structure (Krull *et al*., 2003) [50]. However, the results of many soil studies have shown that the majority of organic materials do not exhibit the chemically and thermodynamically stable properties of earlier models; instead, the factors that primarily influence how long organic materials persist in soil are the physical characteristics that enable them to resist microbial attack (Schmidt *et al*., 2011) [4] (Lehmann and Kleber, 2015) [5].

In both flooded and aerobic systems, one of the most important mechanisms for vegetable organic matter to persist is the protection of SOM within soil aggregates; however, the characteristics and development of soil aggregates in flooded soils versus aerobic soils differ greatly. In aerobic systems, the development of large (>250 µm) macroaggregates, which trap particulate organic matter via roles such as fungal hyphae; root mucilage; and polyvalent cation bridging, isolates POM from microbial attack and allows time for the organic carbon within aggregate protected POM to accumulate over time with a mean residence period of decades to centuries (Sander *et al*., 2014) [21] (Six *et al*., 2002) [51]. In flooded soils, a reduction in macroaggregate stability due to the physical dispersion of clay soils and a reduction in activity from fungal organisms has reduced aggregate protection, while chemical suppression of oxidative enzymes will allow for some aggregation and soil organic matter remains in the soil for comparable lengths of time (Zhang *et al*., 2007) [52].

4.2. Microbial Necromass Contribution to SOM Stabilization

Recent information on dead microbial cells, their membranes and cytoplasm indicates that the majority of stable SOM in mineral soils is derived from these dead cells, with well-studied systems accounting for approximately 50-80% of MAOM (Liang *et al*., 2019) [47] (Miltner *et al*. 2012) [53]. Riverside and paddy soils are continuously replenished with live microbes and decayed material known as necromass containing muramic acid (from bacterial cell walls), glucosamine (from fungal cell walls), and microbial lipids are also very common in these environments (Joergensen 2018) [54]. The microbial carbon pump mechanism indicates that as readily decomposable OC passes through the plant, to microbial and then into necromass state and sorbs onto minerals MAOM is primarily created through the decomposition of plant based readily decomposeable OC, microbial metabolism, and the sorption of necromass onto mineral surfaces (Lehmann and Kleber, 2015) [5] (Liang etal., 2019) [47]. In a flooded environment, bacteria will comprise the majority of the fungal biomass (resulting in a predominance of muramic acid) thus; it has an increased capacity to associate with iron oxide surfaces through the carboxylic and amine functional group (Weiss *et al*., 2003) [34]. In an aerobic environment, the predominant source of necromass is fungal based chitin and preferentially it would not interact with clay minerals but would rather interact via electrostatic means (Amelung *et al*., 2020) [55].

4.3. Aggregate Formation and Occlusion Processes

Soil aggregate (clumping of particles) creation and function are greatly affected by how we manage our soil moisture during rice production. The process of flooding soil causes the formation of microaggregates (2 to 250 microns) through bridging by organo-mineral material (material containing both biological and mineral origins) like iron and aluminum oxides; whereas, at the same time, it destroys macroaggregates (clumps containing <50% clay and 50% loam), which tend to be less stable than microaggregates due to biological activity alone. As noted in Sander *et al*. (2014) [21] and Zhang *et al*. (2007) [52], during AWD rice production or while growing rice in aerobic environments, there is an increase in the level of macroaggregate formation (and thus stability) due to increased colonization of macroaggregates by fungi, greater production of organic matter (mainly sugars) from root systems, and additional cementation of soil particles from minerals resulting from drying soils.

Microaggregates within macroaggregates are thought to show a hierarchy of physical protection between the aggregation of physical protection and the physical and chemical protection of soil organic matter (Six *et al*., 2002) [51]. The microaggregates of soil organic matter that are in close proximity to iron oxide nanoparticles and fine clay minerals are believed to be the most stable due to both forms of chemical and physical protection (Kaiser and Guggenberger, 2000) [42]. When organic matter in this hierarchical arrangement is disturbed (by tillage) or has been exposed for a long time to aerobic conditions, it becomes openly accessible to microbial mineralization because of the migratory nature of their structures (Kuzyakov, 2010) [27].

4.4. Environmental Controls on SOM Turnover Rates

Variability of SOM decomposition in rice agroecosystems occurs as a result of temperature, moisture, pH, and substrate conditions. The temperature coefficient (Q_{10}) is a measure of how fast SOM will decompose with increasing temperature by indicating how many times the rate of decomposition will double with temperature changes. The degree of change in Q_{10} will vary under anaerobic as opposed to aerobic conditions. Under flooded (anaerobic) conditions, Q_{10} ranges from 1.5–2.5, while under aerobic conditions it will be 2.0–3.5. Given these variances in temperature response, anaerobic (flooded) systems will experience a greater loss of OC due to climate change than aerobic systems. This information is vital for modeling and understanding how SOC will change under climate change scenarios. Soil pH affects SOM stability by affecting bonding strength between organic (SOM) and inorganic (mineral) components; therefore, depending on the bonding strength, SOM will decompose at different rates based on its association with soil pH. Buffering of flooded soils occurs around pH 6.5–7.0, providing stable bonding conditions between SOM and mineral soils, while aerobic (non-flooded) soils may experience reduced pH (<5.0) because of increased use/managing of these soils.

5. Mineral Association of Organic Matter in Rice Soils

5.1. Organo-Mineral Interactions: Clay Minerals and Fe/Al Oxides

The interaction between mineral and organic matter in paddy soils involves several bonding mechanisms via which organic functional groups can bind to mineral surfaces; these include electrostatic attraction, van der Waals force, cation bridging, ligand exchange, and hydrophobic interactions. The primary mineral phases which contribute to OC sorption include clay minerals (such as kaolinite, illite, and smectite) and iron/aluminium oxides (for example, goethite, ferrihydrite, and gibbsite). The relative importance of these different mineral phases for OC sorption will depend on the physical and chemical characteristics of the soil, such as its type, mineralogy, and the effect of its redox history (Torn *et al*., 2009) [13].

In Oxisols and Inceptisols, where rice is grown, Fe-oxides represent a key sorptive mechanism for OC. Specifically, ferrihydrite is a poorly crystallised, short-range order (SRO) iron (III) mineral with an extremely high specific surface area (200–800 $m^2\ g^{-1}$) and point of zero charge (PZC ≈ 8.0–8.5), allowing for efficient formation of ligand exchange complexes with negatively charged carboxylate and phenolate functional groups of humic substances (Fimmen *et al*., 2008) [11]. The high concentration of ferrihydrite in the oxidised root zone and in newly drained aerated soils makes Fe-oxides the main OC sorbing phase in these conditions.

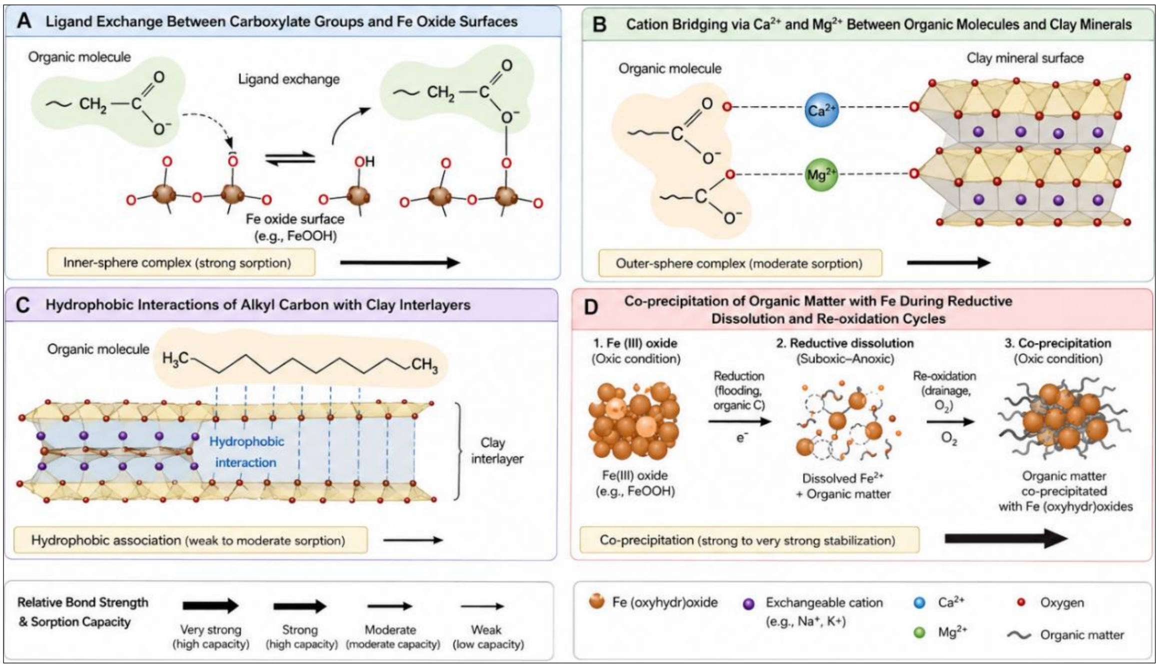


Fig 3: Schematic Representation of Organo–Mineral Interaction Mechanisms in Paddy Soils

5.2. Adsorption, Complexation, and Co-precipitation Mechanisms

Rice soils contain three main mechanisms that regulate how organic carbon (OC) interacts with various types of minerals. The three primary methods are: (1) adsorption (a surface complex is developed between OC and the mineral); (2) complexation (OC is associated with a dissolved cation); and (3) coprecipitation (the OC is integrated into a precipitated phase during the precipitation process). In aerobic systems or conditions, the dominant mechanism by which OC interacts with a mineral in rice soils is by adsorption to stable surface sites on crystalline forms of iron or aluminium oxides. However, there is a significant increase in the significance of coprecipitation (the OC becomes incorporated into a precipitate during the process of iron precipitation) of OC coprecipitated with newly formed iron mineral phases due to hydro-dynamic changes in redox status across the soil during alternating aerobic/anaerobic periods (water management strategy systems) or during seasonal flooded rice paddies. Recent literature shows that OC coprecipitated with iron during the post-flood, re-oxidation period (due to reduced iron being oxidized when it is exposed to atmospheric air after being in an anaerobic (flooded) environment) provides one of the most viable pathways for the long-term stabilization of organic carbon in soils because OC coprecipitated with iron in soils is completely encased in a mineral matrix and is protected from degradation via enzyme-based mechanisms. (Riedel *et al*., 2013) [12]. Using synchrotron X-ray Absorption Spectroscopy, it was shown that organic carbon and iron (as ferrihydrite) form close nanoscale associations that do not easily desorb - even in conditions that promote the dissolution of the mineral. In contrast, organic carbon absorbed by minerals can be displaced by competition with other ligands or as a result of changes in ionic strength of the liquid.

5.3. Role of Short-Range-Order Minerals in SOM Stabilization

The high specific surface areas (far larger than traditional clay) and the high reactivity of the SRO minerals (e.g., imogolite, allophane, ferrihydrite) result in their unique ability to sorb organic carbon (OC) (Torn *et al*. 2009) [13]; thus, they represent a substantial portion (50-80%) of the total OC associated with all minerals in Andisols and the oxidized layers of tropical paddy soils where SRO minerals occur in high levels (10-50 g kg^{-1}). Although the total mass of SRO minerals is relatively small compared to the total volume of soil minerals in Andisols, it has been suggested that the abundance of SRO minerals and the stable OC they create will largely dictate what level of mineral-associated organic matter (MAOM) is present in tropical rice soils and that this generally represents the primary pedological driver of the MAOM inventory within those soils.

SRO mineral cycling is governed by the Fe (iron) redox process; ferrihydrite and OC are released into the soil from the dissolution of ferrihydrite under anaerobic conditions, then incorporated back into ferrihydrite during aeration, which creates OC stabilization within the soil. If, before the formation of the ferrihydrite mineral structure, there were more OC released from the dissolution of OC than what was generated during the formed dissolution of the ferrihydrite mineral structure, then this results in a net stabilization of OC within the soil. Conversely, if before OC was released into the soil, OC was remineralized before the formation of the ferrihydrite mineral structure; this would result in net OC being lost from the soil. Therefore, the degree of uncertainty surrounding the long-term net mass of OC flux in paddy soils is quite high (Kaiser and Guggenberger, 2000) [42].

5.4. Differences in Mineral Association Under Anaerobic vs. Aerobic Regimes

Flooding and non-flooded rice cultivation use different types of water. This means there is a different chemical composition of soils because of the different types of water used. In flooded water systems, soils begin as aerobic (with oxygen) and turn anaerobic (without oxygen). As this happens, crystalline forms of iron minerals (goethite and hematite) change to amorphous forms (ferrihydrite and lepidocrocite) at the same time. As the crystalline iron minerals become more reactive, they promote the adsorption of organic carbon for a short period of time. However, after the initial adsorption period ends, organic carbon will be lost from flooded soils through reductive dissolution of organic carbon bound to iron (Fimmen *et al*., 2008) [11]. The way that MAOM is continuously created and destroyed in flooded paddy soils is different than the way that MAOM is created and destroyed in aerobic rice cultivation and allows for continued accumulation of MAOM in flooded paddy soils.

Aerobic rice systems constantly contain very crystallized Fe oxides (low specific surface area) associated with poor crystallization and well-crystallized Fe oxide, allowing for continuous adsorption of OC onto Fe oxides, thus providing a relatively more stable pool of MAOM that is less sensitive to redox fluxes than would be expected. Other factors contributing to OC retention in aerobic systems are increased clay aggregation and stable OC-clay complexes. Aerobic systems also have significantly greater amounts of MAOM per unit weight of soil than flooded systems; however, aerobic systems have higher rates of microbial OC mineralization than their flooded counterparts and therefore are not as capable of acquiring and retaining OC.

Table 5: Comparative organo-mineral association characteristics in flooded and aerobic Oryza sativa paddy soils across different soil mineralogical classes.

Mineral Type	Mechanism	OC Sorption (mg C g^{-1} mineral)	Flooded Impact	Aerobic Impact
Ferrihydrite (SRO)	Ligand exchange / co-precip.	30–120	Reductive dissolution releases OC	High sorption, stable MAOM
Goethite	Ligand exchange	10–40	Partial reduction	Dominant, stable phase
Kaolinite	Electrostatic / cation bridging	5–20	Stable, clay dispersion	Aggregate formation
Smectite	Interlayer hydrophobic / H-bond	8–30	Swelling, reduced sorption	Stable, high CEC
Allophane (SRO Al)	Ligand exchange / electrostatic	40–150	Relatively stable	Very high sorption
Gibbsite	Ligand exchange	5–15	Stable	Moderate sorption
Calcite (calcareous soils)	Cation bridging (Ca^{2+})	2–10	Dissolution in low pH	Moderate

6. Impact of Water Management Practices on SOM Dynamics

6.1. Continuous Flooding versus Alternate Wetting and Drying

As a result of this alternating flooding-draining method used in rice production, water usage has decreased by approximately 15% to 30%. Although there may be a slight decrease in yields, the use of alternating wetting-drying (AWD) methods to irrigate rice has been widely adopted by rice producers. With AWD systems, paddy soils experience both aerobic (air) and anaerobic (non-air) conditions throughout the cropping season. This alteration in moisture regime creates a different soil organic matter (SOM) dynamic from a continuously flooded or permanently aerobic paddy system. Increased oxidative activity within increased microbial biomass shifts from anaerobic to aerobic decomposer microbes during periods of aerobic and anaerobic conditions. The oxidation of mobilized iron ions during periods of re-oxidation allows for the development of some new mineral surfaces that create bonding sites for organic carbon (OC) sorption.

The net effect of AWD on soil organic carbon (SOC) levels varies by farmer productivity level based on the frequency and depth of wet and dry cycles, soil texture, temperature, and initial SOC level. Through a meta-analysis of long term AWD studies in rice paddies, researchers found that SOC levels may be slightly to moderately lower (by 3% to +5%) than SOC levels found in continuously flooded cropping systems. Regardless of whether there are differences between SOC levels resulting from AWD and continuously flooded systems, the degree to which OC is decomposed and stabilised through the various stages of the AWY crop cycle will have a direct effect on climate-smart rice production.

6.2. Aerobic Rice Cultivation Systems

For instance, aerobically cultivated paddy rice systems (a.k.a., "dryland rice") have been developed as a strategy to cope with water shortages in rice-producing countries across Asia (Bouman *et al*., 2007) [8] (FAO, 2018) [14].

Unlike traditional paddy-based farming systems where rice is grown in flooded, puddled soils, aerobic rice is grown in non-flooded, non-puddled soils under "aerobic" conditions, i.e., without water. Aerobic rice production fundamentally changes the soil environment compared to conventional paddy farming (Kögel-Knabner *et al*., 2010) [15]. This results in rapid decomposition of soil organic matter (SOM), reduced steady-state soil organic carbon (SOC) concentrations, altered mineral weathering regimes and vastly different greenhouse gas (GHG) emissions profiles (Smith *et al*., 2008) [10].

Long-term aerobic rice production systems that have been developed to grow rice in an upland environment have been associated with significant depletion of soil carbon; reported SOC losses of 15-40% relative to flooded control systems have been observed over a 5-10 year period (Pan *et al*., 2010) [3] (Lu *et al*., 2009) [28]. However, due to increased stability in macroaggregates formed under aerobic conditions and the potential for deep storage of organic carbon (OC) at deeper soil horizons, some of the OC depleted from surface soils may be compensated for by the storage of OC in deeper soil layers (Six *et al*., 2002) [51]. Given that the sustainability of aerobic rice production systems from a soil carbon standpoint will depend on the integrated management of organic amendments and the continued promotion of aggregate stability, management practices will be important.

6.3. Effects on SOM Stabilization, Decomposition, and Nutrient Cycling

In terms of several critical processes, the different effects of various water management regimes on the stabilization of SOM and nutrient cycling are summarized below. Rates of nitrogen mineralization in aerobic systems are considerably greater due to active nitrification and aerobic decomposition of organic nitrogen substrates. As a result of these two processes, nitrogen that is available to plants in the short term is generally higher than in anaerobic systems, while nitrogen retention efficiency is typically lower and N2O emissions higher than in anaerobic systems (Aulakh *et al*., 2001) [49].

Phosphorus cycling is strongly affected by the dissolution and precipitation of Fe-P complexes that are dependent on the reduction-oxidation (redox) state of the soil and, under flooded conditions, inundated soils have a greater capacity to release plant available phosphorus from reductively dissolved Fe phases than do drained soils (Reddy and DeLaune, 2008) [9]. Sulfur cycling under anaerobic conditions is accomplished through the sulfate to sulfide (H2S) reduction process, which can lead to the formation of metal precipitates with Fe2+ and other heavy metals that impact the availability of trace metals and organic matter binding (Lovley and Goodwin, 1988) [39]. As these processes also are dependent on the availability of oxygen, sulfur will be oxidized rapidly under aerobic conditions and this rapid oxidation may contribute to soil acidification in certain soils (Ponnamperuma, 1972) [16]. The linkages of sulfur, iron and carbon cycling in rice soils create a complex biogeochemical continuum that requires a systems approach to fully understand the mechanisms operating in long-term rice production (Kögel-Knabner *et al*., 2010) [15].

Table 6: Effects of water management practices on key soil organic matter and nutrient cycling parameters in Oryza sativa cultivation systems.

Parameter	Continuous Flooding	Alternate Wetting & Drying	Aerobic Cultivation
SOC stock change (%/decade)	+5 to +15	−3 to +5	−15 to −40
N mineralization rate	Low (anaerobic)	Moderate (pulsed)	High (aerobic)
P availability	High (Fe-P dissolution)	Moderate (variable)	Low–moderate (sorption)
Aggregate stability (MWD)	Moderate (1.2–2.0)	High (2.0–3.5)	Very high (2.5–4.5)
Enzyme activity (overall)	Low (suppressed)	Moderate (pulsed peaks)	High (continuous)
Fe oxide crystallinity	Low (amorphous dominant)	Mixed (cycling)	High (crystalline)
Microbial biomass (mg C kg^{-1})	200–600	350–750	400–900
Water use (mm season^{-1})	1000–2000	700–1400	400–800
CH_4 emission (kg ha^{-1} season^{-1})	80–400	30–120	<5
N_2O emission (kg N ha^{-1} season^{-1})	<0.5	0.5–1.5	1.0–3.0

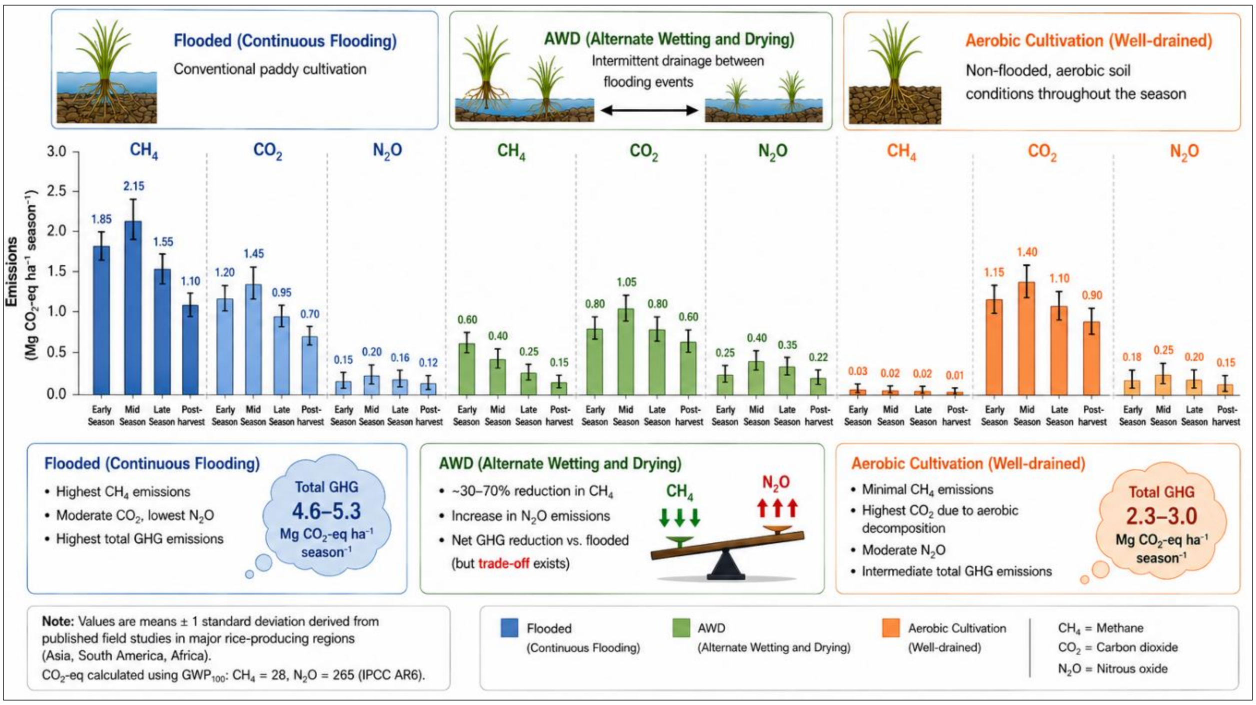
7. Carbon Sequestration and Greenhouse Gas Emissions

7.1. Methane Emissions Under Flooded Conditions

Paddies that are flooded have become the world's largest agricultural contributor to methane emissions. An estimated 25–36 Tg of methane are produced annually (or about 10% of all anthropogenic methane emissions) due to this source (Yan *et al*., 2005) [20] (Smith *et al*., 2008) [10]. The methane production that occurs in paddy soils is attributable to methanogenic bacteria known as hydrogenotrophic methanogens (H2/CO2) and Acetesclasts (which use acetate) that utilize H2 and CO2, respectively. These two groups of methanogenic bacteria consume substrates (hydrogen (H2) and carbon dioxide (CO2)) derived from the fermentation of SOM and inputs of organic matter are the two groups of methanogenic bacteria that contribute to CH4, or methane, production in paddy soils (Conrad, 2009) [38] (Yao *et al*., 1999) [40]. Methane emissions from paddy soils are positively correlated with total available dissolved organic matter, input of fresh organic materials to paddy soils, soil temperature, and length of time that flooding occurs. Conversely, the supply of Fe3+ and sulfate are negatively correlated with methane emissions from paddy soil (Lovley and Goodwin, 1988) [39]. While the majority of CH4 emissions from paddy soils are created by methanogenic bacteria, a portion of the CH4 created will be oxidized by methanotrophic bacteria in the rhizosphere (the area immediately surrounding the roots of the plant) and at the soil-floodwater interface (Conrad, 2009) [38]. Rice varieties chosen as cultivars for growth in AWD (alternate wetting and drying) conditions affect CH4 emissions via the different aerenchyma development (the pathway for CH4 transport from the soil to the atmosphere), exudate composition produced from the roots, and oxidation capacity of the rhizosphere (Colmer, 2003) [30]. With the introduction of new rice varieties that were created for use in AWD systems and to help with the mitigation of CH4 emissions while yielding similar crops, researchers have found that this is a large opportunity to reduce global methane emissions (Sander *et al*., 2014) [21].

7.2. CO_2 and N_2O Emissions Under Aerobic Systems

Flooded systems produce methane (CH_4) emissions, while those of aerobic rice crops have much lower emissions than flooded systems but produce greater emissions of carbon dioxide (CO_2) from mineralisation of soil organic matter (SOM) and nitrous oxide (N_2O) from nitrification and denitrification (Smith *et al*., 2008) [10]. The total net CO_2 produced by an aerobic rice system is estimated to be 2–5 times greater than for a flooded rice paddy, primarily due to the increased rate at which the SOC originally present in the soil is oxidised or decomposed (Inubushi *et al*., 2003) [46]. If global warming potentials are applied to these GHGs (GWP: CH_4 × 28; N_2O × 265; over a 100 year period) and added together, the defined total radiative forcing of the aerobic rice crop will be comparable to or exceed that of the flooded rice crops under certain climatic and environmental conditions (Smith *et al*., 2008) [10]. Using partially-reduced conditions created by runoff and organic matter accumulation in soil to produce N_2O from nitrification-denitrification processes; and chemical denitrification in organic-rich microsites are two processes that produce the N_2O emitted from aerobic rice systems (Aulakh *et al*., 2001) [49]. Estimates of the N_2O emission factor for aerobic rice are subject to greater uncertainty because of the high temporal and spatial variability; however, most values currently published are in the range of 0.5–2.0% of applied N-fertiliser, which is used for comparison purposes to N_2O emission factors associated with other aerobic cereal crop production systems. A major issue to be addressed while developing climate-smart rice production systems is the trade-off of reduced emissions of CH_4 from back inundation, but increased emissions of N_2O from aerobic rice production (Smith *et al*., 2008) [10].



Flooded (Continuous Flooding)

- Highest CH_4 emissions
- Moderate CO_2, lowest N_2O
- Highest total GHG emissions

AWD (Alternate Wetting and Drying)

- ~30–70% reduction in CH_4
- Increase in N_2O emissions
- Net GHG reduction vs. flooded (but trade-off exists)

Aerobic Cultivation (Well-drained)

- Minimal CH_4 emissions
- Highest CO_2 due to aerobic decomposition
- Moderate N_2O
- Intermediate total GHG emissions

Note: Values are means ± 1 standard deviation derived from published field studies in major rice-producing regions (Asia, South America, Africa).
CO_2-eq calculated using GWP_{100}: CH_4 = 28, N_2O = 265 (IPCC AR6).

Fig 4: Comparative Greenhouse Gas (GHG) Emission Profiles of Flooded, Alternate Wetting and Drying (AWD), and Aerobic *Oryza sativa* Cultivation Systems

7.3. Carbon Balance and Sequestration Potential

Rice agroecosystems have been evaluated for their overall net carbon balance based on the amount of organic carbon (OC) being input and output through the following:

- Inputs are created using plant residues (dead plants), root biomass (living plants), and organic amendments (chemicals or products made from organic matter) (Jones *et al*., 2009) [29] (Lu *et al*., 2009) [28].
- Outputs can come from carbon dioxide (CO2) respiration, methane (CH4) emissions, or dissolved organic carbon (DOC) leaching. (Smith *et al*., 2008) [10]

Flooded paddies have been known as large-scale carbon sources for many years — documented SOC accumulation rates from long-term experiments have ranaged from 0.1 to 0.5 Mg C ha-1 yr-1 throughout Asia and beyond. (Pan *et al*., 2010) [3] However, due to high CH4 emissions when pads are continuously flooded, most grow systems have now converted from being net greenhouse gas (GHG) sinks in terms of CO2 to being GHG sources over a 100-year GWP basis. (Smith *et al*., 2008) [10]

Ensuring that the carbon sequestration potential of rice soils is optimized will require developing strategies that are capable of:

- Reducing GHG emissions and increasing SOC accumulation simultaneously; and
- Providing a dual-benefit strategy such as using biochar amendments, which provide a stable carbon source, while reducing CH4 and N2O emissions; (Lehmann and Kleber, 2015) [5] and
- Affecting OC input rates through enhanced nutrient cycling efficiencies via integrated organic and mineral nutrient management, which will improve SOC retention without raising GHG emission rates relative to that of OC inputs. (Amelung *et al*., 2020) [55]

Table 7: Carbon balance components and net greenhouse gas budget for Oryza sativa cultivation systems under contrasting water management regimes.

Carbon/GHG Component	Continuous Flooding	AWD	Aerobic	Unit
SOC input (plant residue)	3.0–6.0	3.0–6.0	2.5–5.0	Mg C ha^{-1} yr^{-1}
SOC mineralization (CO_2)	1.5–3.0	2.0–4.0	3.5–6.0	Mg C ha^{-1} yr^{-1}
Net SOC change	+0.1 to +0.5	−0.1 to +0.2	−0.3 to −1.5	Mg C ha^{-1} yr^{-1}
CH_4 emission (C-equiv.)	0.5–3.0	0.2–1.0	<0.05	Mg C ha^{-1} season^{-1}
N_2O emission (CO_2-equiv.)	<0.2	0.2–0.6	0.4–1.2	Mg CO_2-eq ha^{-1} season^{-1}
Total GHG budget (CO_2-eq.)	6–20 (source)	4–12 (moderate)	4–10 (lower CH_4)	Mg CO_2-eq ha^{-1} yr^{-1}
DOC leaching	0.05–0.2	0.03–0.1	0.01–0.05	Mg C ha^{-1} yr^{-1}

8. Experimental and Analytical Approaches in Paddy SOM Research

8.1. Soil Fractionation Techniques

Ecological relevant soil organic matter fractionation through physical methods (fractionating soil into SOM pools defined operationally, in terms of biological availability, mean residence time, and mineral association) includes the use of density fractionation techniques to separate free light (fLF), occluded light (oLF), and heavy soil organic matter (HF SOM). The fLF and oLF are free or occluded to the soil solid phase, respectively, while the HF SOM, or mineral-associated OC (one or more minerals + OC), is generally bound within the soil solid structure (Christensen, 2001) [22]. Tools such as sodium polytungstate or sodium iodide are used in this density fractionation process (density ranges of 1.6–2.0 g/cm³) against the separation of soil organic matter based upon mineral association and/or biological availability (Golchin *et al.*, 1994) [23]. This method is particularly useful for following OC stabilization under different redox conditions in paddy soils (Kögel-Knabner *et al.*, 2010) [15].

As part of locating OC associated with specific mineral phase identification, sequential extractions are also utilized for the extraction (separating) of organically complexed Fe/Al, amorphous Fe/Al oxide minerals (including ferrihydrite), and crystalline oxides from paddy soils using sodium pyrophosphate, ammonium oxalate, and citrate-bicarbonate-dithionite (CBD) as extraction solvents. This sequential extraction method is an effective way to evaluate/regulate OC association to minerals and associated biological availability (Riedel *et al.*, 2013) [12] (Kaiser and Guggenberger, 2000) [42]. By integrating the information obtained from the physical and chemical fractionation data (i.e., physical fractionation = locate and quantity of cation associated with OC) will result in the total OC distribution among the mineral phase and protectiveness of OC in paddy soils.

8.2. Isotopic Tracing Methods

Using ^{13}C and ^{15}N stable isotope analysis, entering the dynamics of carbon and nitrogen in an individual paddy soil system can be accomplished with a high degree of resolution. Through natural abundance discrimination in ^{13}C between the parallel C_3 (rice, $\delta^{13}C \approx -27‰$) and C_4 plants that are often grown prior to rice (or as amendments) we are able to distinguish between plant derived and soil-derived soil organic carbon (SOC) fractions without placing isotopic labels on any substrates. Compound specific isotopic analysis (CSIA) of specific organic compounds within each SOC fraction (e.g., phospholipid fatty acids, amino sugars) allows us to ascertain the contribution of each to soil organic matter (SOM) (Amelung *et al.*, 2020) [55].

Isotopic labeling of ^{13}C and ^{15}N will allow identification of organic derived carbon from specific sources (^{13}C-labeled straw) or origins (^{15}N-urea) in SOM fractions, in microbial biomass, and in green-house gas (GHG) emissions through controlled incubation or field experiments (Kuzyakov and Xu, 2013) [6] (Jones *et al.*, 2009) [29]. In particular, isotopic labeling has provided considerable evidence for the rapid immobilization of root exudate derived carbon into MAOM within a few weeks following the addition of readily available carbon, and the differential allocation of fresh carbon to stable vs. labile pools under flooded versus aerobic conditions (Liang *et al.*, 2019) [47] (Kuzyakov, 2010) [27]. Since we are capable of using radiocarbon (^{14}C) to measure carbon isotopes found in bulk and particle size fractionated organic carbon, we can establish absolute chronological limits on the mean residence times of both total and fractionated organic carbon pools (Torn *et al.*, 2009) [13].

Table 8: Summary of isotopic tracing and spectroscopic techniques applied to soil organic matter dynamics in Oryza sativa paddy systems.

Technique	Target Information	Spatial/Temporal Resolution	Key Application in Rice Soils
Natural ^{13}C abundance	C_3/C_4 OC partitioning	Bulk soil, fractions	Plant OC source tracing
^{13}C pulse labeling	Fresh C allocation & fate	Days–months	Rhizodeposition, MAOM formation
^{15}N isotope dilution	N mineralization rates	Weeks–seasons	N cycling under redox change
^{14}C radiocarbon dating	Mean residence time	Decades–millennia	MAOM age, stable pool characterization
Solid-state ^{13}C NMR	C functional group chemistry	Bulk SOM composition	Lability and recalcitrance assessment
FTIR spectroscopy	Organic functional groups	µm–mm scale	Organo-mineral bonding characterization
X-ray photoelectron spectroscopy (XPS)	Surface C and Fe speciation	Surface (<10 nm)	Fe-OC surface complexes
Synchrotron XANES/EXAFS	Metal-OC coordination	Nanometer scale	Fe oxide OC association mechanisms
CSIA (PLFA, amino sugars)	Microbial biomarker tracing	Bulk fractions	Necromass contribution to MAOM
Nano-SIMS	Element distribution at nm scale	Nanometer scale	OC-mineral co-localization

8.3. Spectroscopic and Molecular Techniques

Cross-Polarization Magic Angle Spinning Nuclear Magnetic Resonance Spectroscopy is a Non-destructive means to determine Bulk SOM Functional Group Chemistry and to distinguish between Alkyl-C, O-Alkyl-C (carbohydrates), Aromatic-C, and Carboxyl-C....Studies conducted on the OC Chemistry of Paddy Soils using NMR have found consistent differences in OC Chemistry for Flooded vs Aerated Systems with Flooded Paddy Soils showing Higher O-Alkyl-C/Alkyl-C Ratios that are indicative of Less Processed Organic Matter (Olk *et al.*, 2006) [26].

Synchrotron-Based X-Ray Absorption Near-Edge Spectroscopy and Extended X-Ray Absorption Fine Structure Spectroscopies Provide Molecular-Level Information on the Coordination Environment of Fe In Soil Samples, Thus Enabling the Discrimination of Ferrihydrite, Goethite, and Other Phases of Fe and Their Spatial Association With Organic Carbon (Fimmen *et al.*, 2008) [11]. Nano-scale Secondary Ion Mass Spectrometry Imaging is a Visual Method That Allows For Direct Visualization of Co-localization of Elements at Nanometer Resolution Thus Providing Strong Evidence of Close Association of Organic Carbon-Fe Minerals in Paddy Soils (Riedel *et al.*, 2013) [12].

8.4. Microbial Ecology Tools

Studies utilizing shotgun metagenomics and amplicon sequencing of phylogenetic markers (16S rRNA for bacteria/archaea, ITS for fungi) have provided a comprehensive examination of the composition of microbial communities and the functional gene diversity found within paddy soil samples (Zhang *et al.*, 2018) [19] (Breidenbach *et al.*, 2016) [48]. In addition to these metagenomics studies, functional gene arrays (GeoChip) that target key genes involved in carbon cycling (e.g. cbh1, nifH, mcrA, pmoA), nitrogen cycling (e.g. amoA, nirS, nosZ), and metal cycling can be utilized to examine functional metabolic potential in soils that have different types of redox conditions (Nealson and Stahl, 1997) [37]. Enzyme activity assays targeting specific hydrolytic and oxidative enzymes (e.g. cellulases, proteases, phenol oxidases, N-acetyl glucosaminidases) provide an integrated measure of the functional metabolic capacity found in paddy soils (Sinsabaugh *et al*., 2009) [44] (Kang *et al*., 2011) [45]. Enzyme kinetic parameters (Vmax, Km) that are derived from substrate concentration/activity curves provide essential information needed for constructing decomposition models that will be used to parameterize soil organic matter — SOM — turnover within biogeochemical simulation models. The combination of metagenomics with targeted enzyme assays will provide additional insights into the mechanisms that connect microbial community structure to SOM transformation rates in paddy soils that are subject to different water management strategies.

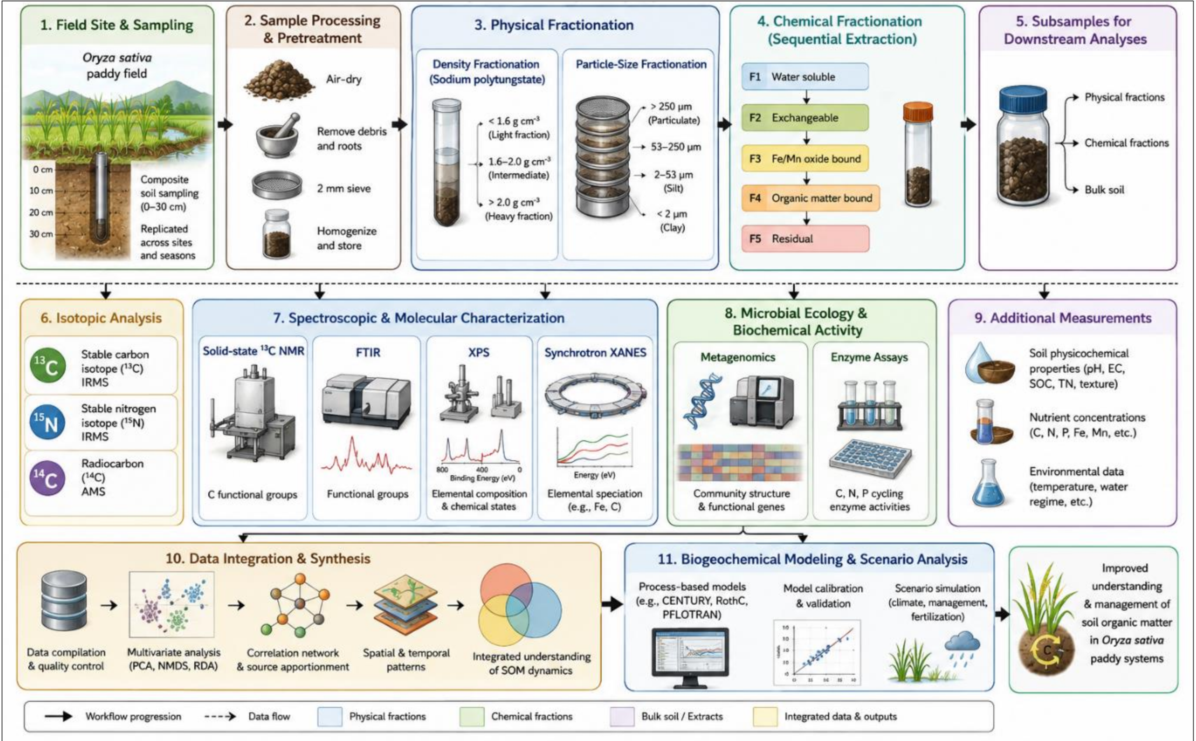


Fig 5: Experimental workflow for comprehensive analysis of soil organic matter dynamics in Oryza sativa paddy systems

Table 9: Soil fractionation methods and associated organic carbon data reported from paddy soils under contrasting water management in major rice-producing regions.

Study Location	Soil Type	Fractionation Method	Flooded OC (g kg⁻¹)	Aerobic OC (g kg⁻¹)	MAOM% (Flooded)
China (Yangtze Delta)	Gleysol	Density + size	22.4±3.1	14.2±2.0	68
India (Tamil Nadu)	Inceptisol	Chemical sequential	18.6±2.4	11.5±1.8	62
Japan (Hokkaido)	Andosol	Density fractionation	35.2±4.8	21.8±3.5	74
Philippines (IRRI)	Vertisol	Size fractionation	16.9±2.2	12.1±1.5	60
Brazil (Rio Grande)	Ferralsol	Density + chemical	19.4±3.0	13.6±2.1	65
Bangladesh (Sylhet)	Fluvisol	Chemical fractionation	24.1±3.6	16.8±2.3	70

9. Agronomic and Environmental Implications

9.1. Soil Fertility and Nutrient Use Efficiency

The differing dynamics of soil organic matter in flooded versus aerobic rice production systems have direct impacts on soil fertility and plant nutrient availability. For instance, with continuous flooding, the higher concentrations of soil organic carbon (SOC) in these environments provide higher cation exchange capacity (CEC), greater water-holding capacity, and longer duration of nitrogen and phosphorus availability to plants via the mineralization of organic matter throughout the growing season. However, because ammonium (NH_4^+) predominates as the mineral form of nitrogen when rice is grown under flooded conditions, there are many challenges associated with managing nitrogen fertilizer because, under alkaline soil conditions (i.e., high pH), NH_4^+ can volatilize into ammonia, and during the short periods of aerobic conditions that occur during the flooded to non-flooded cycle, nitrification-denitrification processes can take place.

There may be benefits with regard to greater rates of nitrogen mineralization from soil organic matter with aerobic rice production that could help to lower nitrogen fertilizer input needs in the short term; however, with the progressive decline of SOC due to continued aerobic rice production, the long-term nitrogen supply function and resiliency of the soil will be diminished by this reduction in SOC (Kögel-Knabner *et al*., 2010) [15] (Amelung *et al*., 2020) [55]. As a result, there are ongoing research efforts aimed at optimizing the integration of organic and mineral nutrient management strategies for aerobic rice (Amelung *et al*., 2020) [55] to ensure that adequate SOC stocks remain through the implementation of sustainable management practices, i.e., applying organic amendments and minimizing tillage.

9.2. Sustainable Rice Production Strategies

Producing rice sustainably means farmers must get the most crops grown in an environmentally friendly way while keeping soil healthy fact that there are many different climates around the world.

One-way farmers can produce sustainable rice is through integrated soil-water-nutrient management, which use a common combination of optimised irrigation schedules (alternate wet-dry), a proper balance of nutrients with both organic and inorganic fertiliser, water-efficient but productive varieties of rice, and how to recycle leftover crop waste materials back into the field as 'green' manure. All these methods will help them to sustainably increase their rice yield (FAO, 2018) [14] (Amelung *et al*., 2020) [55].

The System of Rice Intensification (SRI) or "more productive ways to grow rice", which relies on using dry soils, lower seed densities, and organic materials to increase the amount of rice that can be produced per acre and reduce the amount of water used and greenhouse gases emitted by planting rice in many cases (Bouman *et al*., 2007) [8]. We need to research how soil organisms and chemical properties interact when using SRI so we can better understand how the results of SRI vary from one location to another to provide local farmers with better advice on how to improve their yields sustainably through managing their soils (Kögel-Knabner *et al*., 2010) [15].

9.3. Integration of Organic and Inorganic Amendments

The combination of organic amendments - including compost, crop residues, green manures, and biochar - with mineral fertilisers is a key component in sustainably managing soils for rice agroecosystems (Amelung *et al*., 2020) [55]. Although organic amendments supply nutrients to crops, they also provide a range of other functions; for example, enhancing the accumulation of soil organic matter (SOM), improving the physical properties of soils, stimulating the development of beneficial microbial communities, and modulating redox dynamics of flooded soils (Lehmann and Kleber, 2015) [5]. The interaction of the timing, placement, and chemistry of organic amendments with soil mineralogy and management of water to which those amendments are exposed will determine their overall effect on stabilising SOM and emission of greenhouse gases (Kögel-Knabner *et al*., 2010) [15].

Biochar is an important source of an organic amendment for rice systems because it is produced by pyrolysis of organic materials and has a unique recalcitrant aromatic carbon structure (it can last from centuries to thousands of years), has a very large surface area that provides sites for sorption of organic carbon (OC), and is effective at reducing the amount of CH_4 emitted from flooded rice systems by 10% to 40% (Lehmann and Kleber, 2015) [5]. However, the long-term impacts of biochar on soil mineralogy, organo-mineral associations, and microbial community structure are not yet fully understood, and studies are needed across contrasting rice cultivation systems.

9.4. Policy Relevance and Climate-Smart Agriculture

The Paris Agreement's National Determined Contributions (NDCs) and other associated initiatives, like the Food and Agriculture Organization's (FAO) Climate Smart Agriculture (CSA) framework and the Global Research Alliance on Agricultural Greenhouse Gases, have significant implications for rice-growing countries as they relate to management practices and systems for growing rice (FAO, 2018) [14] (Amelung *et al*., 2020) [55]. The quantification of greenhouse gas (GHG) mitigation potential from improved water management practices, particularly alternate wetting and drying (AWD), has led to Measurement, Reporting, and Verification (MRV) protocols for developing carbon credit programs targeting rice (Smith *et al*., 2008) [10].

Monetizing soil carbon via voluntary carbon markets and results-based climate financing provides economic incentives for farmers to diversify their cropping systems or plant different crops than they previously did by encouraging them to implement practices that increase soil organic matter (SOM) levels in the soil and reduce GHG emissions (Amelung *et al*., 2020) [55]. However, there continues to be a need to improve the scientific basis of quantifying soil carbon in rice systems based on durability of MAOM under climate change scenarios, how paddy soil carbon stocks respond to increasing intensity of water management, and how biochar and native SOM interact with each other in the context of the various soil mineralogies in which they occur (Lehmann and Kleber, 2015) [5] (Kögel-Knabner *et al*., 2010) [15].

Table 10: Summary of nutrient cycling parameters under contrasting water management strategies in Oryza sativa paddy systems, with implications for soil fertility and fertilizer management.

Nutrient Parameter	Continuous Flooding	Alternate Wetting & Drying	Aerobic Rice
NH_4^+-N availability	High (accumulation)	Pulsed (moderate)	Low (rapid nitrification)
NO_3^--N availability	Very low (<2 mg kg⁻¹)	Moderate (5–20 mg kg⁻¹)	High (20–80 mg kg⁻¹)
N_2O emission potential	Low (<0.5 kg N ha⁻¹)	Moderate (0.5–1.5)	High (1.0–3.0)
Plant-avail. P (mg kg⁻¹)	15–50 (Fe-P release)	10–30 (variable)	5–20 (sorption)
K availability	Moderate	Moderate	High (leaching risk)
Fe availability (mg kg⁻¹)	High (>100, phytotoxic)	Moderate (20–60)	Low (<10)
Zn availability	Low (sulfide precip.)	Moderate	Moderate–high
N use efficiency (%)	30–50	40–60	35–55
Recommended N fertilizer	Reduced (NH_4 stable)	Standard	Increased (mineralization)

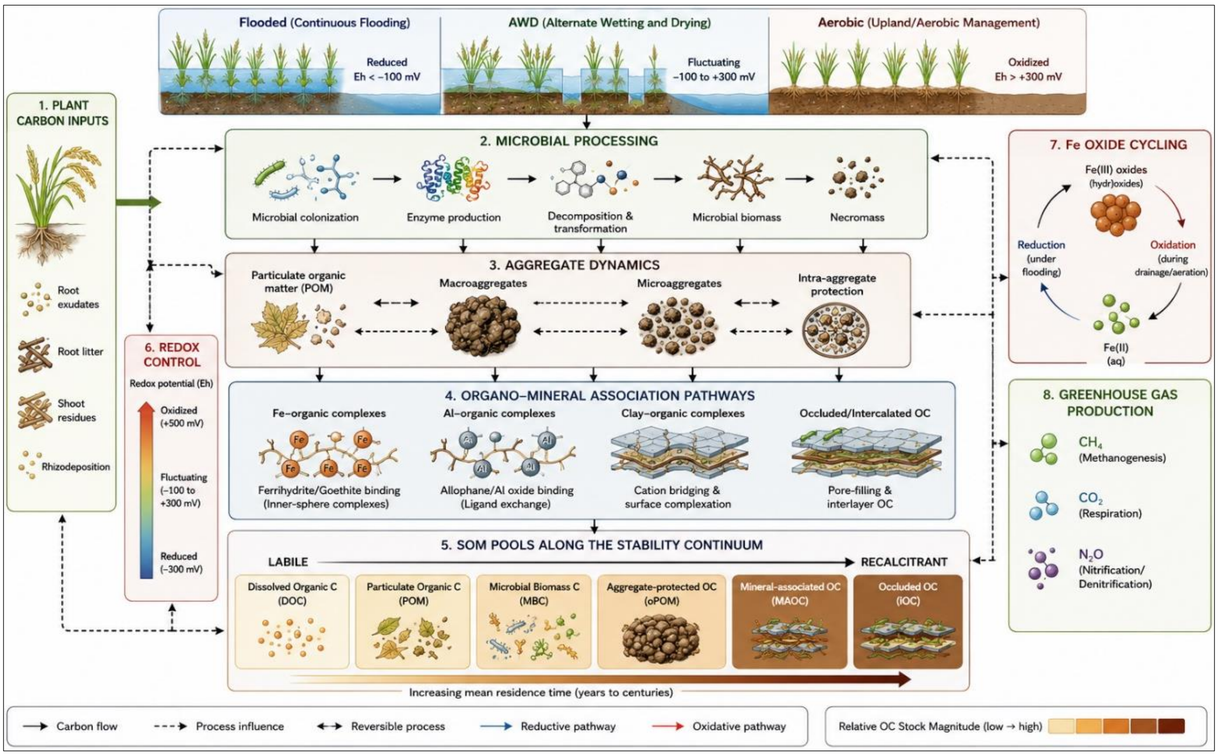


Fig 6: Integrated soil organic matter (SOM) stabilization model for Oryza sativa paddy soils

Table 11: Carbon sequestration potential and greenhouse gas mitigation options across Oryza sativa water management strategies, with estimated implementation feasibility and cost-effectiveness.

Strategy	SOC Sequestration Potential	CH_4 Reduction	N_2O Change	Implementation Feasibility	Co-benefits
Alternate wetting & drying (AWD)	Neutral to slight gain	30–50%	+50–150%	High (proven technology)	Water saving, yield neutral
Biochar amendment	High (persistent C addition)	10–40%	−20–30%	Moderate (cost, availability)	Soil health, fertilizer efficiency
Organic residue incorporation	Moderate	0 to +20%	Neutral	High (common practice)	Nutrient cycling, soil structure
Aerobic rice (upland)	Negative (SOC loss)	~95% reduction	+100–200%	Moderate (water saving)	Water efficiency, labor reduction
Deep water management	High SOC under flooding	Baseline CH_4	Low N_2O	Low (water-limited regions)	Flood risk management
Crop rotation (legume)	Moderate (N input)	Variable	Moderate increase	Moderate	Soil N fertility
Precision N fertilization	Neutral	Minor	−30–50%	Moderate–high	Reduced pollution, cost

10. Conclusion

The findings of this comprehensive review synthesised newly acquired knowledge regarding the formation of soil organic matter (SOM) and its association with minerals as a result of flooded and aerobic cultivation of Oryza sativa; i.e. concepts prepared in one Paper (Soil Biogeochemistry, Microbial Ecology and Soil Minerals Used in the Cultivation of Rice), utilizing a mechanistic strategy with respect to the integration and correlation of information from soil biogeochemistry, microbial ecology, mineralogy, and agronomy. The synthesis yields the following overall conclusions.

Although flooded cultivations cause an increase in SOM via reducing oxidative enzyme activities and generating, accumulating, and recycling a number of anaerobic fermentation byproducts, and producing reactive Fe mineral surfaces via the dynamic cycling of Fe minerals, the amount of SOM generated in flooded paddies is predominantly in the form of mineral-associated organic matter (MAOM), which accounts for 60–75% of the total soil organic carbon (SOC), is primarily in association with short-range-order Fe phases, and is also the primary reservoir for long-term C storage in the flooded rice paddies.

Although aerobic cultivations increase the rate at which SOM is mineralised, they also provide opportunities to form stable macroaggregates and create stable organo-clay associations, which will partially offset the increased decomposition rates of SOM associated with aerobic cultivation of rice. Aerobic pathways of decompostion of SOM, however, result in a net loss of soil organic carbon (SOC) of 15–40% over a multi-year timespan, although the long-term storage of stable soil organic carbon (SOC) deep (i.e., 50-100 cm) in the subsoil, combined with enhanced interactions between organics and the clay mineral (OC-clay) two-dimensional lattice structure of the soil matrix, may help to mitigate some of the SOC losses.

The practice of alternating periods of wetting and drying rice paddies offers a practical trade-off, reducing methane (CH_4) emissions by 30-50% compared to continuously flooding rice paddies while largely maintaining soil organic carbon (SOC) stocks and represents the most viable option available at the current time to simultaneously address issues of water scarcity, mitigate greenhouse gases (GHGs), and preserve soil carbon in rice agroecosystems. Nitrogen management practices and site-specific evaluation will be essential due to the potential increased nitrous oxide (N_2O) emissions due to the use of alternative wetting and drying rice paddies.

Microbial necromass is a major pathway for stable soil organic matter (SOM) development in both flooded and non-flooded rice systems, as it is produced by the mechanism known as the microbial carbon pump. No evidence to suggest that the composition of necromass (i.e., the ratio of bacterial to fungal biomass) nor the affinity of necromass for different mineral phases, is consistent across redox (oxygen) conditions, which results in the development of very different mineral-associated organic matter (MAOM) chemistries that will have different degrees of resistance to decomposition.

There are research gaps that require urgent attention: (1) an evaluation of how long MAOM will remain stable over time with changes in climate-caused hydrology and increasing frequency of drought events; (2) the quantification of how much, if at all, the iron-organic carbon (OC) co-precipitation mechanism contributes to OC net stabilization over multiple dissolution-precipitation cycles; (3) the role of the microbial community in mediating the efficiency of the microbial carbon pump based on the type of water management regime used; and (4) the interaction between biochar amendments, native SOM, and iron mineral cycling in various paddy soil mineralogical environments.

To create a climate-smart rice crop that not only produces high yields but also captures Carbon and reduces GHG emissions will take site-specific combinations of optimized forms of water management (AWD), targeted organic amendments, improved rice varieties and precise nutrient management. To achieve the full benefits of rice agroecosystems toward achieving global climate stabilization will require improved scientific and policy infrastructure to support these practices including effective soil carbon monitoring and MRV systems.

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