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Regenerative Soil Health Management in Rice Cultivation: Principles, Practices, Trade-offs, and Future Directions

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Abstract

Rice cultivation supports global food security but is increasingly constrained by soil organic matter depletion, nutrient imbalance, declining water availability, biodiversity loss, and greenhouse-gas emissions. Regenerative soil health management seeks to restore soil functions while maintaining yield, profitability, and resilience. This review synthesizes evidence on the principles, practices, benefits, limitations, and future priorities of regenerative management in rice-based systems. The principal practices include reduced soil disturbance, residue retention and recycling, crop rotation, cover and green-manure crops, integrated nutrient management, compost and biochar application, alternate wetting and drying (AWD), System of Rice Intensification principles, integrated weed management, and biological inputs. These interventions can improve soil organic carbon, aggregate stability, nutrient-cycling capacity, microbial activity, water productivity, and yield stability. However, outcomes are context-dependent. AWD generally reduces methane but may increase nitrous oxide; fresh straw incorporation improves carbon inputs but can intensify methane production; zero tillage can initially increase surface compaction; and organic amendments may be limited by labour, transport, nutrient uncertainty, contaminants, and competing uses. Regenerative rice management should therefore be understood as an adaptive portfolio rather than a universal package. Future research should prioritize long-term farmer-managed trials, standardized soil-health indicators, whole-system greenhouse-gas accounting, food-safety assessment, economic risk analysis, and digital decision-support systems.

Keywords: *rice; soil health; regenerative agriculture; conservation agriculture; soil organic carbon; alternate wetting and drying; residue management; biochar; nutrient cycling; climate-smart agriculture.*

1. Introduction

Rice (*Oryza sativa* L.) is cultivated across tropical, subtropical, and temperate environments and remains central to food security, rural employment, and cultural systems. Intensification has often relied on repeated puddling, continuous flooding, monocropping, high mineral-nitrogen inputs, and heavy pesticide use. Over time, these practices may contribute to declining soil organic carbon (SOC), structural degradation, nutrient imbalance, compaction, acidification, salinity, loss of soil biodiversity, and inefficient water and nutrient use [1–6]. Rice soils are biogeochemically distinctive. Alternating flooded and drained conditions create redox gradients that regulate carbon decomposition, nitrogen transformations, phosphorus availability, iron and manganese chemistry, arsenic mobility, and methane formation. Thus, an intervention that improves one function may impair another. Drainage can reduce methane but stimulate nitrification and denitrification, potentially increasing nitrous oxide emissions [7–11].

Regenerative agriculture has no universally accepted operational definition. It generally refers to management intended to restore soil biological activity, improve physical and chemical function, increase biodiversity, reduce unnecessary external inputs, and strengthen farm resilience [12–14]. This review examines regenerative soil health management in rice cultivation, emphasizing principles, practices, trade-offs, and future research priorities.

2. Principles of regenerative rice management

2.1 Soil as a living system

Soil health includes physical, chemical, and biological dimensions. Relevant indicators in rice systems include SOC, particulate organic matter, aggregate stability, bulk density, infiltration, pH, electrical conductivity, available nutrients, microbial biomass, enzyme activity, earthworm abundance, and nutrient-use efficiency [12,15,16].

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Regenerative management treats these indicators as interconnected: carbon inputs influence aggregation and microbial activity; microbial processes regulate nutrient availability; soil structure controls water movement; and water regime determines redox conditions and greenhouse-gas production.

2.2 Continuous cover and carbon inputs

Residues, living roots, cover crops, green manures, and diversified rotations protect the surface and increase carbon transfer to soil. However, carbon input does not automatically mean permanent sequestration. Under flooded conditions, a fraction of readily decomposable carbon may be converted to methane, while long-term SOC accumulation depends on input quality, stabilization, decomposition, erosion, and gaseous losses [17–20].

2.3 Minimal disturbance with functional soil preparation

Reduced tillage can conserve aggregates, reduce fuel consumption, protect fungal networks, and preserve surface carbon. In rice-based systems, conservation agriculture commonly combines reduced disturbance, residue retention, and crop diversification. A large South Asian synthesis reported benefits for yield, water-use efficiency, economic return, and greenhouse-gas performance, although outcomes differed among crops and environments [21,22]. Rice-specific implementation must account for puddling, drainage, soil texture, seedling establishment, and weed management.

2.4 Diversification and biological regulation

Rotations with wheat, maize, pulses, oilseeds, vegetables, or forage crops can interrupt pest cycles, diversify root systems, alter residue quality, and improve nutrient cycling [23–26]. Legumes may contribute biologically fixed nitrogen, but benefits depend on biomass, nodulation, residue management, and subsequent crop demand. Fish–rice, duck–rice, and habitat-management approaches may increase biodiversity but require assessment of competition and labour.

2.5 Context-specific nutrient and water cycling

Regenerative management does not imply that all mineral fertilizers should be eliminated. In many rice systems, targeted mineral nutrients remain necessary to avoid yield decline and nutrient mining. The objective is to synchronize nutrient supply with crop demand through the right source, rate, time, and placement, while increasing recycling through residues, compost, manures, biological fixation, and improved nutrient-use efficiency [27–30].

3. Major regenerative practices

3.1 Residue retention and straw management

Rice straw contains carbon, potassium, silica, and smaller amounts of nitrogen and phosphorus. Retention and recycling can increase SOC, improve aggregate stability, reduce erosion, and return nutrients, while avoiding air pollution from burning [1,21,31].

However, straw incorporated shortly before flooding supplies readily decomposable carbon and may increase methane. It can also temporarily immobilize nitrogen, delay crop establishment, obstruct machinery, and increase pest pressure [17,18,32].

Practical options include chopping and uniform spreading, early incorporation, composting, partial aerobic decomposition, conversion of a portion to biochar, and retaining residues for the following crop. The appropriate strategy depends on methane risk, livestock demand, machinery, nutrient replacement, and possible contaminants. Straw return may mobilize cadmium in contaminated paddies, requiring soil and grain monitoring [33].

3.2 Reduced tillage and conservation agriculture

Conservation agriculture generally combines minimal soil disturbance, soil cover, and crop diversification [21,22]. In rice–wheat systems, zero-till wheat after rice can reduce fuel use and shorten the interval between crops [21,34]. Potential benefits include greater aggregation, particulate organic matter, microbial biomass, and infiltration. Limitations include initial surface compaction, penetration resistance, weed pressure, residue-related pests, and machinery constraints, particularly in poorly drained soils [22,34].

3.3 Cover crops and green manures

Cover crops protect soil during fallow periods and provide carbon and nutrients. Legumes such as Sesbania, mung bean, cowpea, and clovers may supply nitrogen, whereas non-legumes produce fibrous biomass and improve structure [23–26]. Constraints include dry-season water use, competition for land, pest carryover, labour, and temporary nitrogen immobilization. Low-carbon-to-nitrogen-ratio residues may increase nitrous oxide where mineral nitrogen accumulates under fluctuating moisture [9,35].

3.4 Integrated nutrient management

Rice requires nitrogen, phosphorus, potassium, sulfur, zinc, and silicon. Excessive nitrogen lowers nitrogen-use efficiency and can increase ammonia volatilization, nitrate loss, nitrous oxide, lodging, and disease susceptibility [27–30]. Recommended measures include soil-test-based fertilization, balanced nutrients, split nitrogen application, deep placement, controlled-release fertilizers, nitrification inhibitors, compost, and safe recycling of residues. Nutrient balances should account for straw removal for feed, fuel, or other uses.

3.5 Organic amendments and compost

Compost, farmyard manure, vermicompost, poultry manure, and anaerobic-digestion residues may improve SOC, cation-exchange capacity, water retention, aggregation, and microbial activity [36–38]. Their nutrient content varies widely, and immature materials may contain pathogens, weed seeds, phytotoxic compounds, salts, or heavy metals. Manures and readily decomposable materials may increase ammonia, methane, or nitrous oxide under flooded conditions [17,32,36].

Amendments should be selected using analysis of carbon, nutrients, pH, electrical conductivity, maturity, contaminants, and pathogens.

3.6 Biochar

Biochar can increase pH, cation-exchange capacity, porosity, water retention, and carbon persistence. A quantitative review reported increases in rice yield and nitrogen-use efficiency of approximately 10.73% and 12.04%, respectively, although responses varied with feedstock, pyrolysis temperature, soil type, application rate, and water regime [39]. Biochar effects on methane and nitrous oxide are inconsistent [40–42]. Poor-quality biochar may contain heavy metals or polycyclic aromatic hydrocarbons, and high application rates may be uneconomic.

3.7 Alternate wetting and drying irrigation

AWD replaces continuous flooding with controlled irrigation and drying cycles. It can reduce water use, improve aeration, and suppress methanogenesis [7–11]. A global meta-analysis reported that AWD reduced methane by 51.6%, increased nitrous oxide by 44.0%, and reduced global warming potential by 46.9% relative to continuous flooding [10]. Another synthesis reported methane reduction of 43.23%, nitrous oxide increase of 42.59%, and global warming-potential reduction of 36.84% [11].

AWD depends on soil texture, percolation, rainfall, irrigation infrastructure, cultivar, residue management, nitrogen timing, and land levelling. Severe drying can reduce yield, increase weeds, and alter arsenic dynamics [7,43]. Field water tubes and protection from water stress during flowering and grain filling are essential.

3.8 System of Rice Intensification

SRI combines young seedlings, wider spacing, reduced seedling injury, intermittent irrigation, mechanical weeding, and greater use of organic matter. A review of Chinese evidence reported yield advantages exceeding 10% over improved conventional practices [44]. However, SRI outcomes vary because the term encompasses different combinations of practices and because comparisons often differ in fertilizer, cultivar, irrigation, and labour.

3.9 Biological inputs

Biofertilizers and microbial inoculants include nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium-mobilizing bacteria, arbuscular mycorrhizal fungi, and plant-growth-promoting rhizobacteria [45–47]. Potential mechanisms include nitrogen fixation, phosphate solubilization, phytohormone production, pathogen suppression, and improved root development. Field performance is less consistent than greenhouse performance because introduced microorganisms must compete with native communities and tolerate variable redox, salinity, pH, temperature, and pesticide exposure.

3.10 Integrated weed and pest management

Cultural methods include competitive cultivars, optimum density, stale seedbeds, crop rotation, synchronized planting, mechanical weeding, residue mulching, and water-level management [48–50]. Herbicides remain useful, especially in direct-seeded rice, but repeated use of the same modes of action increases resistance risk. Integrated management should combine cultural, mechanical, biological, and chemical methods with resistance monitoring.

4. Soil-health outcomes and trade-offs

Residues, roots, compost, and reduced tillage can improve aggregate stability, porosity, infiltration, water-holding capacity, and erosion resistance [15,21,34]. Improvements may require several years, and surface residues may temporarily lower soil temperature or interfere with machinery. In poorly drained soils, reduced tillage may increase near-surface compaction unless drainage, deep rooting, controlled traffic, or occasional strategic tillage is used.

Organic inputs generally increase SOC, total nitrogen, cation-exchange capacity, and nutrient buffering [31,36–38]. Conversely, repeated mineral nitrogen application without balanced nutrient replacement or liming can contribute to acidification [51]. Flooding changes phosphorus, iron, manganese, and arsenic chemistry; AWD may reduce arsenic accumulation in some contexts but requires site-specific monitoring [43].

Regenerative practices can increase microbial biomass, enzyme activity, fungal networks, earthworms, and functional diversity [12,15,16,23]. Nevertheless, salinity, acidity, pesticide exposure, excessive ammonium, and prolonged anaerobic conditions can constrain biological recovery.

Rice management should account for methane, nitrous oxide, and carbon dioxide together. Continuous flooding and readily decomposable organic inputs generally increase methane, while drainage and nitrogen application may increase nitrous oxide [7–11,17,35]. Climate performance should therefore be assessed using net global warming potential and yield-scaled emissions rather than methane alone.

Regenerative practices may improve yield stability and reduce costs after establishment, but transition costs can include machinery, labour, technical management, temporary yield penalties, and uncertain market premiums. Economic evaluation should include labour, water, fertilizer, machinery, residue opportunity cost, yield risk, and long-term soil benefits.

5. Context-specific implementation framework

A practical framework should follow five stages. First, diagnose soil texture, drainage, pH, electrical conductivity, SOC, nutrients, compaction, water quality, residue availability, weeds, and crop history. Second, design a complementary portfolio rather than adopting isolated technologies. Third, implement gradually, beginning with low-risk changes such as soil testing, split nitrogen, improved water scheduling, and residue distribution. Fourth, monitor SOC, aggregate stability, bulk density, infiltration, pH, nutrients, microbial indicators, yield, water productivity, nitrogen-use efficiency, greenhouse gases, and gross margin.

Fifth, adapt the system through feedback when practices cause excessive methane, weed pressure, delayed establishment, or flowering-stage water stress [12–14,52].

6. Future directions

Future research should prioritize long-term, multi-location, farmer-managed trials across irrigated, rainfed, upland, coastal, acidic, saline, and flood-prone systems [12–14]. A minimum rice soil-health dataset should include total and particulate SOC, aggregate stability, bulk density, pH, electrical conductivity, mineral nitrogen, available phosphorus and potassium, microbial biomass, infiltration, methane, nitrous oxide, yield, water productivity, and profitability.

Digital tools, sensors, remote sensing, field water tubes, and decision-support systems can improve site-specific water and nutrient management [27,52]. However, tools must be affordable, locally validated, and accessible to smallholders. Microbiome-informed management, synthetic microbial communities, beneficial endophytes, and improved biofertilizer formulations deserve further field validation [45–47].

Whole-system life-cycle assessment should include field emissions, fertilizer manufacture, irrigation energy, residue management, labour, machinery, soil-carbon permanence, food safety, biodiversity, yield, and economic distribution [12–14,53]. Carbon-credit systems should account for methane, nitrous oxide, leakage, permanence, and uncertainty rather than rewarding SOC increases alone.

Policy support should include soil testing, residue-management machinery, water-user associations, crop diversification, extension, credit, local composting and biochar enterprises, insurance, and markets for sustainably produced rice. Incentives should reward verified outcomes such as improved soil function, reduced water use, lower net greenhouse-gas intensity, and stable yields.

7. Conclusions

Regenerative soil health management in rice cultivation is a context-specific process of restoring soil functions while maintaining productivity, profitability, food safety, and environmental quality. Its central principles are continuous carbon inputs, reduced disturbance, diversified cropping, biologically active soils, efficient nutrient and water cycling, and adaptive management.

The strongest evidence supports integrated portfolios that combine residue and nutrient management, crop diversification, reduced tillage where appropriate, precise nitrogen application, and carefully managed AWD. No practice is universally beneficial: straw can build SOC while increasing methane; AWD can reduce methane while increasing nitrous oxide; organic amendments can improve fertility while introducing emission, nutrient, salinity, or contaminant risks; and conservation agriculture can reduce disturbance while increasing short-term management complexity.

Regenerative rice cultivation should therefore be promoted as an evidence-based and locally adapted pathway rather than a universal recipe. Long-term evidence, standardized indicators, farmer-centred experimentation, whole-system greenhouse-gas accounting, and policies that reduce transition risk are essential for successful scaling.

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