Research Progress on Management and Utilization of Cold Waterlogged Paddy Fields in Jiangnan (Postprint)

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Abstract

Cold waterlogged paddy fields represent a major category of low-yielding paddy fields in the Jiangnan region of China, which have attracted considerable attention due to their widespread abandonment, yet enormous potential for yield improvement and superior natural ecological conditions. The formation of cold waterlogged paddy fields results from the combined effects of climate, topography, hydrology, and human management. Under the influence of perennial surface water and groundwater waterlogging, the soil physical, chemical, and biological properties of cold waterlogged paddy fields have undergone a series of changes, exhibiting obstacle characteristics of "cold, muddy, toxic, and infertile," including low water and soil temperature, low soil immersion bulk density, high contents of reductive substances such as ferrous iron, organic acids, and reduced sulfur, high organic carbon content but deficiency or imbalance of active organic carbon and available nutrients, and sparse microbial flora. Cold waterlogged paddy fields can be diagnosed and soil quality assessed through indicators such as the gleyic horizon of paddy fields, soil reductive substances, and groundwater level. The management and utilization of cold waterlogged paddy fields involve integrated technologies including engineering measures, agronomic measures, and biological measures, encompassing open ditches and underground pipes, suitable varieties, paddy-upland rotation, ridge-furrow cultivation, balanced fertilization, and soil amendments. In addition to traditional rice cultivation methods, site-specific utilization constitutes an effective measure for enhancing the comprehensive production capacity of cold waterlogged paddy fields. Building upon previous research and from the perspective of agricultural sustainable development, future research priorities and countermeasure suggestions for the management and utilization of cold waterlogged paddy fields are proposed, including investigating differences in soil structure and soil organic matter fractions under various waterlogging states and dry-wet alternations; strengthening research on methane emission characteristics from cold waterlogged paddy fields under long-term waterlogging conditions; enhancing ecological process studies on anaerobic microorganisms and their related enzymes produced during the gleyization process of cold waterlogged paddy fields, and strengthening microbiological regulation to improve cold waterlogged paddy fields; furthermore, technical integration and policy support should be enhanced for cold waterlogged paddy fields with different ecological types and production conditions.

Full Text

Preamble

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A review on improvement and utilization of southern cold-waterlogged paddy fields in China

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Abstract: Cold-waterlogged (CW) paddy fields represent the primary low-yield paddy fields in South China. These fields have attracted considerable attention due to their widespread abandonment, substantial yield improvement potential, and favorable natural ecological conditions. The formation of CW paddy fields results from complex interactions among climate, topography, hydrology, and anthropogenic management. Influenced by perennial surface water and groundwater saturation, the physicochemical and biological properties of CW paddy field soils exhibit systematic changes characterized by "cold, muddy, toxic, and infertile" constraints: low water and soil temperatures, low immersed bulk density, high concentrations of reductive substances such as ferrous iron, organic acids, and reduced sulfur, high organic carbon content but low active organic carbon and deficient or imbalanced available nutrients, and diminished microbial flora. Soil quality of CW paddy fields can be diagnosed and evaluated using indicators including gleyic horizons, soil reductive substances, and groundwater levels. Integrated management and utilization of CW paddy fields encompasses engineering, agronomic, and biological measures, including open ditches and subsurface drainage pipes, suitable crop varieties, paddy-upland rotation, ridge cultivation, balanced fertilization, and soil amendments. Beyond traditional rice cultivation, site-specific utilization represents an effective approach to comprehensively enhance the productive capacity of CW paddy fields. Based on previous research and from the perspective of sustainable agricultural development, this review identifies future research priorities and policy recommendations, including: (1) investigating differences in soil structure and organic matter composition under various waterlogged conditions and dry-wet alternations; (2) strengthening research on methane emission characteristics in long-term waterlogged CW paddy fields; (3) enhancing ecological process studies of anaerobic microorganisms and associated enzymes during the gleyization process to improve microbial regulation for CW paddy field amelioration; and (4) strengthening technology integration and policy support tailored to different ecological types and production conditions.

Keywords: Cold-waterlogged paddy field; Soil amendment; Obstruction factor; Improvement and utilization; Sustainable development

1. Overview of Cold-Waterlogged Paddy Fields in Jiangnan

Cold-waterlogged paddy fields refer to a type of paddy field characterized by long-term water saturation, exhibiting "cold, muddy, toxic, and infertile" features. These fields are primarily distributed in mountainous hilly valleys, low-lying areas of plains and lake marshes, and lower sections of reservoirs and dam areas. The total area of cold-waterlogged paddy fields in Jiangnan exceeds 2 million hectares, with larger concentrations in Jiangxi, Hunan, Fujian, Yunnan, Guizhou, Sichuan, Guangdong, and Guangxi provinces (autonomous regions), and additional distribution in Zhejiang, Hubei, Anhui, Jiangsu, and Taiwan.

The redox potential is significantly reduced, generally below 150 mV, and soil profiles appear bluish-gray, creating cold, muddy, and toxic conditions unfavorable for crop growth and development. From an agricultural production perspective, cold-waterlogged paddy fields are predominantly located in hilly mountainous regions with scattered farmland, poor transportation infrastructure, and weak irrigation systems. Water layers remain in continuous flood irrigation, and some drainage canals become blocked due to disrepair, causing secondary gleyization. Overall, cold-waterlogged paddy fields exhibit multiple obstacle factors, extensive but rough cultivation practices, and low yields. Research indicates that rice yields in cold-waterlogged paddy fields are 1,500–2,250 kg · hm ^{2} lower than in conventional paddy fields.

Cold-waterlogged paddy fields, as a conventional term, belong to the gleyic paddy soil subgroup in the Chinese Soil Classification System and correspond to the Stagnic Gleyic or Orthic Gleyic suborders in the Chinese Soil Taxonomy System. According to formation conditions and soil profiles, *An Introduction to China' s Agricultural Soil* classifies cold-waterlogged paddy fields into five types: muddy fields, cold water fields, cold bottom fields, toxic fields, and highland cold-waterlogged fields. Gong Zitong et al. categorized gleyic paddy soils into five types based on the position, thickness, and development degree of diagnostic gleyic horizons: whole-layer gleyic, upper-position gleyic, lower-position gleyic, plow-pan gleyic, and middle-position gleyic. Recent studies have also proposed alternative classifications from a management perspective, dividing non-plow-pan cold-waterlogged fields into mountain valley muddy fields, low-lying muddy fields, and rusty water muddy fields, while plow-pan cold-waterlogged fields are preliminarily classified into low-lying cold water fields, calcareous cold water fields, muddy cold water fields, sandy cold water fields, and mineral-toxic cold water fields.

2. Main Obstacle Factors of Cold-Waterlogged Paddy Fields in Jiangnan

The formation of cold-waterlogged paddy fields results from comprehensive interactions among climate, topography, hydrology, and anthropogenic management. Climatically, southern provinces are rich in water resources, with surface runoff from large catchment areas and abundant groundwater converging in low-lying areas. Topographically, cold-waterlogged paddy fields typically occur in narrow, undulating mountain valleys of southern China. For example, in Fujian, the valley openness ratio (valley width/relative height) is often less than 5, resulting in short sunshine duration due to high mountains and forest shade, and low water and soil temperatures. Hydrologically, these fields are often irrigated with cold mountain spring water or have high seepage rates, with groundwater levels typically above 50 cm and sometimes overflowing to flood paddy fields. This creates a dominant reducing environment that intensifies the reduction and leaching of iron and manganese oxides, leading to soil disintegration, poor structure, and increased ferrous and manganous content. The redox potential decreases significantly, generally below 150 mV, and soil profiles appear bluish-gray, creating cold, muddy, and toxic conditions unfavorable for crop growth.

2.1 Physical Obstacle Factors

Cold-waterlogged paddy fields experience perennial waterlogging, differing from gray-muddy paddy fields in two key aspects: higher groundwater levels and more stable groundwater fluctuations, unlike the frequent fluctuations in percolating paddy fields such as gray-muddy fields that develop distinct illuvial horizons. Among cold-waterlogged field types, cold water fields with lower soil temperatures also cause plant growth disorders. Observations show that total sunshine hours during the rice growing season (June–October) in mountain valley bottoms amount to 612.3 h, 217.6 h less than in plain fields (a 26.2% reduction). Water and soil temperatures in spring-mouth cold water fields are 4.5–8.2 °C and 4.9–8.7 °C lower than in plain fields, respectively. Monitoring of cold-waterlogged and non-cold-waterlogged fields in similar topographic settings reveals that during the single-season rice growth period (June–October), average surface temperature and soil temperatures at 5 cm, 10 cm, and 15 cm depths are 0.4 °C, 0.4 °C, 0.5 °C, and 0.6 °C lower than in gray-muddy fields, respectively, with the temperature difference increasing further during the heading and grain-filling stages in September–October. Thus, high groundwater levels accompanied by strong reducibility, lower photosynthetically active radiation, and rapid soil temperature decline during late rice growth stages constitute important habitat characteristics distinguishing cold-waterlogged from non-cold-waterlogged fields. Consequently, increasing environmental soil temperature represents a key entry point for managing and utilizing cold-waterlogged paddy fields.

Soil structure forms the foundation for maintaining soil function. In water-saturated cold-waterlogged paddy fields with intense gleyization, colloids absorb water, swell, and become highly dispersed, forming structureless, muddy layers. For example, in Fujian’ s deep muddy fields, the muddy layer exceeds 30 cm in thickness, sometimes reaching 100 cm. Once drained and dried, these soils become sticky, hard, and develop wide cracks upon desiccation. Upon re-wetting, they settle and harden into rigid clumps that impede rice root growth and reduce yields. Mechanistically, perennial waterlogging maintains soil metal oxides in a reduced state, preventing them from acting as cementing agents for soil aggregates and resulting in soil disintegration. The muddy, structureless soil in cold-waterlogged fields remains in a “slurry” state, leading to low immersed bulk density. Additionally, because cold-waterlogged soils shrink significantly during air-drying, potentially exhibiting abnormal aggregation, researchers have explored analyzing soil aggregate structure using fresh soil samples.

2.2 Chemical Obstacle Factors

Reductive substances constitute an important characteristic of cold-waterlogged paddy field soils. A survey across seven provinces in Jiangnan revealed average ferrous iron content of 1,437.08 mg · kg^{1} in cold-waterlogged fields, significantly higher than the 814.38 mg · kg^{1} in high-yield fields. In typical Fujian cold-waterlogged fields, ferrous iron content is 177% higher than in non-cold-waterlogged fields (gray-muddy and yellow-muddy fields). Chen et al. demonstrated that the critical concentration of ferrous iron causing toxicity stress to rice growth and microbial activity is 300 mg · kg^{1} (including background). High Fe^{2} concentrations significantly inhibit rice shoot and root growth and reduce chlorophyll content in lower leaves. When Fe^{2} concentration in the medium is excessive, activities of peroxidase (POD), catalase (CAT), and nitrate reductase (NR) in rice are significantly suppressed, whereas at low concentrations, these enzyme activities increase, possibly representing an adaptive mechanism against ferrous toxicity. Excessive Fe stress also inhibits rice shoot and root growth and N, P, and Mg uptake while promoting Cu absorption. Additionally, Fe stress disrupts the distribution balance of available nutrients (P, K, Mg, Zn) between roots and shoots, exacerbating Fe toxicity. The impact of Fe^{2} on rice physiological activity primarily occurs during the tillering and heading stages, with leaves and roots being particularly susceptible during tillering.

Besides reductive minerals like ferrous and manganous ions, the main reductive organic acids in cold-waterlogged fields are formic and acetic acids, whose contribution to grain yield constraints is higher than ferrous iron but lower than manganous ions. Reduced sulfur in cold-waterlogged soils (1,353.01 mg · kg^{1}) far exceeds that in high-yield paddy soils (380.68 mg · kg^{1}), leading to formation of toxic hydrogen sulfide, which partially escapes from the soil and partially dissolves in soil water. Xie et al. identified 40 mg · kg^{1} (including background) as the critical S^{2} concentration causing significant negative effects on the soil-rice-microbial system, necessitating appropriate agronomic measures when exceeded. However, research on hydrogen sulfide toxicity to rice physiology in cold-waterlogged fields remains limited compared to ferrous iron toxicity.

Available phosphorus and potassium contents in cold-waterlogged soils are significantly lower than in non-cold-waterlogged soils, inducing rice akagare disease. Xiang et al. found that groundwater level changes significantly affect nutrient availability, with soil available N and P decreasing as groundwater levels rise. In waterlogged gleyed soils, Fe-P and O-P contents also tend to decrease with rising groundwater levels and are significantly lower than in non-waterlogged soils, reducing P availability. Low P availability in cold-waterlogged soils is also manifested in stronger P adsorption capacity. Studies show that long-term flooded rice-rice-fallow soils have significantly greater P sorption capacity than rice-rice-green manure and rice-rice-rapeseed treatments, with organic manure application and high groundwater levels also enhancing P sorption capacity. This suggests that rotation improves P fertilizer efficiency while organic manure and high groundwater reduce it. Low available nutrients in cold-waterlogged soils also appear at the microelement level. Research indicates that cold-waterlogged and muddy fields in red soil hilly regions have relatively low available sulfur content, presenting potential sulfur deficiency requiring sulfur fertilizer application. Available silicon in gleyed paddy soils is also generally lower than in non-gleyed soils, making silicon deficiency likely.

Organic matter is an important indicator for evaluating soil fertility. High organic matter content is typically considered indicative of productive soils, but cold-waterlogged fields present an exception. While cold-waterlogged soils have high organic matter content, active organic carbon components such as microbial biomass carbon and dissolved organic carbon are significantly lower than in non-cold-waterlogged fields. Thus, for cold-waterlogged fields, active organic carbon fractions better reflect soil quality and improvement effects. Studies on humus composition in cold-waterlogged soils show that gleyed paddy soils are dominated by tightly bound humus of poor quality, whereas percolating paddy soils are dominated by loosely and stably bound humus of better quality. The C/N ratio of organic matter in gleyed paddy soils typically exceeds 12, wider than in percolating paddy soils. Therefore, activating organic matter represents an approach for ameliorating cold-waterlogged fields.

2.3 Biological Obstacle Factors

Accompanying increased reductive substances, microorganisms in cold-waterlogged paddy field soils exhibit unique characteristics. Measurements show that bacterial, actinomycete, and fungal populations in cold-waterlogged fields are significantly lower than in conventional paddy fields, particularly aerobic microbial physiological groups, with weak activity of free-living nitrogen-fixing bacteria and cellulose decomposers and low ammonification intensity, resulting in organic matter accumulation exceeding mineralization. Compared to bacteria, fungi and actinomycetes in cold-waterlogged soils are more susceptible to soil physicochemical factors. Regarding soil enzyme activities, urease activity in gleyed paddy soils is lower than in non-gleyed paddy soils, whereas polyphenol oxidase and iron reductase activities show the opposite trend. Analysis of surface soils from typical cold-waterlogged and non-cold-waterlogged fields within the same micro-landform unit in Fujian revealed that cold-waterlogged fields have 31.7% higher total organic matter, 58.3% and 22.1% higher catalase and invertase activities, but 47.8% and 66.6% lower phosphatase and nitrate reductase activities, respectively, and 29.8%-46.0% lower microbial population counts. Soil nematode community composition and ecological indices can reflect soil health to some extent. A survey of soil nematodes across eight provinces in Jiangnan indicated a density of 344 individuals · (100g)^{1} (dry soil) in cold-waterlogged fields, only 48.04% of that in non-cold-waterlogged fields, demonstrating compromised soil health from a faunal perspective.

2.4 Diagnosis and Quality Assessment of Cold-Waterlogged Paddy Fields

From a diagnostic taxonomic perspective, the gleyic horizon serves as the diagnostic horizon for cold-waterlogged paddy fields, typically appearing bluish-gray with profile configurations of Ag-G, A-G, or A-(Ap)-G types. Based on the unique physical, chemical, and biological properties of cold-waterlogged fields, Xiong et al. proposed that active reductive substances, ferrous iron, Eh, groundwater level, soil color, soil texture, and the activation degree, free degree, and gleyic degree of iron oxides could serve as diagnostic indicators for gleyic soils. Wang et al. established a minimum dataset for soil quality assessment of mountainous cold-waterlogged paddy fields in Fujian, comprising six factors (C/N ratio, bacteria, microbial biomass nitrogen, total reductive substances, physical sand particles, and total phosphorus) through principal component analysis combined with correlation analysis and expert evaluation. Other studies suggest that the minimum dataset for assessing gleyed paddy soil (cold-waterlogged field) quality in subtropical regions includes available potassium, total nitrogen, microbial biomass carbon, total bacteria, -glucosidase, and arbuscular mycorrhizal fungi, with soil quality indices derived therefrom showing significant positive correlation with rice yield. Since these evaluation factors encompass physical, chemical, and biological indicators, they can assess the effectiveness of field management practices and provide early warning of soil gleyization. However, they also reveal that factor selection may vary across different regional scales due to differences in soil properties and utilization patterns. Additionally, since soil microorganisms are sensitive to quality changes in cold-waterlogged fields, scientific criteria for grading based on microbial indicators remain to be established. Furthermore, integrating cold-waterlogged field quality assessment results with Geographic Information Systems (GIS) technology to guide improvement practices at specific field locations represents a future direction for quality evaluation.

3. Improvement and Utilization Measures for Cold-Waterlogged Paddy Fields in Jiangnan

Cold-waterlogged paddy fields possess substantial yield improvement potential. Estimates suggest that comprehensive measures can increase rice yield by 100 kg per 666.7 m^2 annually, translating to an additional 6 million tons of rice from 4 million hectares nationwide. Based on integrated management experience, comprehensive approaches can be developed from engineering, agronomic, and biological measures.

3.1 Engineering Measures

Ditching and subsurface pipe drainage represent fundamental measures for cold-waterlogged field management. Engineering drainage can significantly reduce total soil reductive substances while increasing cation exchange capacity, available phosphorus, and total nitrogen content. Practical experience demonstrates that constructing "four ditches" (flood interception ditches, spring drainage ditches, drainage ditches, and irrigation ditches) to discharge "four waters" (mountain floodwater, cold spring water, toxic rusty water, and serial irrigation water) effectively prevents floodwater entry, retains fertilizer water, diverts cold springs, and removes toxic substances. In mountainous areas of southern Anhui, ditching lowered the groundwater table from 38 cm to 56 cm, increased iron-manganese mottles in the 19–43 cm soil layer, and significantly improved soil nutrient status. In Qingyuan County, Zhejiang, multi-perforated plastic corrugated pipes were used to improve mountainous cold-waterlogged fields, raising soil and water temperatures, improving physicochemical properties, increasing single-season hybrid rice yield by 47.3% compared to unimproved controls, and recovering 37.4% of renovation costs through net profits. In Fujian's mountainous regions, stone-lined deep narrow ditches have proven effective, lowering groundwater levels by 30–50 cm in the third year after implementation. After 30 years of continuous drainage, these ditches remain functional, with soil types gradually evolving from deep muddy fields → shallow muddy fields → gleyed fields → gleyed-bottom gray-muddy fields at distances of 75 m (CK), 25 m, 15 m, and 5 m from ditches. Proximity to ditches correlates with lower reductive substances and higher available N, P, and K contents, as well as higher urease, acid phosphatase, and nitrate reductase activities. Fungal populations also vary significantly with distance from drainage ditches, with highest bacterial diversity at 25 m and highest fungal diversity at 5 m. TGGE fingerprinting reveals that bacterial bands representing certain groups gradually weaken with increasing distance from ditches, indicating decreasing aerobic bacteria and increasing anaerobic bacteria at 75 m. Fungal bands are most abundant nearest the ditch but decrease sharply thereafter, indicating substantial drainage effects on fungi. Additionally, wetland farmland drainage systems with "three ditches" (main, branch, and furrow ditches) accelerate removal of field waterlogging, lower groundwater levels, improve soil permeability, increase nutrients, and promote rice growth and yield. While engineering measures address root causes, agronomic and biological measures should be emphasized in remote mountainous areas with limited capital investment.

3.2 Agronomic Measures

Increasing phosphorus and potassium fertilization represents a key measure for improving cold-waterlogged field productivity. Phosphorus application effects are particularly pronounced in gleyed soils, with yield increases of 8%–20%. Potassium application significantly improves redox properties of lowland gleyed soils, reducing total reductive substances, active reductive substances, and Fe^2 content, thereby alleviating toxicity and increasing rice yield. Li et al. demonstrated that potassium application promotes K uptake and inhibits Fe accumulation in plants, reducing root Fe content at tillering, booting, and maturity stages, making it an effective measure for realizing production potential. Research suggests optimal fertilizer rates for cold-waterlogged fields in low-mountain areas of southeastern Hubei are N 180 kg · hm ^{2}, P O 90–108 kg · hm ^{2}, and K O 120–144 kg · hm ^{2}. In mountainous southern Anhui, 75 kg · hm ^{2} P application optimizes P accumulation across growth stages, increasing tiller number and filled grains per panicle, with calcium magnesium phosphate outperforming superphosphate. Xu et al. recommended fertilizer rates of 11–13 kg N, 3–4 kg P, and 8–11 K per 666.7 m^2 through 3414 regression optimization trials. Additionally, appropriate micronutrient application enhances rice yield. Adequate Ca^2 supply increases or maintains superoxide dismutase, peroxidase, and catalase activities at high levels while maintaining low malondialdehyde content, improving japonica rice tolerance to excessive Fe^2 stress by enhancing reactive oxygen scavenging and biomembrane stability, suggesting potential for calcareous minerals in amelioration. Zinc fertilizer application outperforms sulfur fertilizer, with ZnSO superior to ZnO, and increases N, P, and K use efficiency.

For cultivation improvement, ridge cultivation significantly promotes macroaggregate formation, increases soil temperature, suppresses post-tillering Fe^2 accumulation, reduces root toxicity, enhances enzyme activity, and increases available nutrients compared to conventional flat cultivation. Rice-fish co-culture has minimal impact on physicochemical properties but significantly increases available nutrients, promotes rice growth, and increases yield. After 60 days of ridging, soil Fe^2 content decreases with increasing ridge height. Xiong et al. identified 15 cm as the optimal no-tillage ridge height for cold-waterlogged fields. Combining engineering drainage with ridge cultivation yields the most pronounced effects, increasing yield by 1.11–1.89 t · hm ^{2} per season. Ridge cultivation combined with wet irrigation represents a suitable water management practice for early rice in cold-waterlogged fields.

For lightly gleyed cold-waterlogged fields, paddy-upland rotation effectively enhances productivity. Xiang et al. found that moderate gleyed paddy soils after rotation exhibit increased bulk density and aeration porosity. In gleyed fields, rice-corn, rice-rapeseed, and rice-broad bean rotations show abundant iron-manganese mottles at harvest, with reduced water-stable macroaggregates (>2 mm) and increased microaggregates (<0.25 mm) in topsoil. All rotation patterns gradually decrease active reductive substances while increasing available nutrients and microbial biomass C, N, and P, demonstrating gleyic alleviation and significantly improving total crop yield and economic benefits.

Amendments can improve physicochemical properties and productivity. Oxygen-releasing peroxides in strongly reduced soils significantly improve redox conditions, reduce Fe^2 toxicity, and promote normal rice growth and yield increase. Root oxygenation through peroxides increases early tillering, effective panicles, and root volume at full heading while maintaining high superoxide dismutase and peroxidase activities and low malondialdehyde content in flag leaves, enhancing post-heading photosynthetic contribution to panicle dry matter accumulation. Biochar application increases early soil temperature, promotes rice growth, and increases yield by 8.7%-14.8%. Under dry-wet alternation, fly ash and composite amendments (fly ash + biochar + polyacrylamide) promote macroaggregate formation in two cold-waterlogged soil types. Combined lime and straw application significantly increases Eh while reducing active reductive substances and Fe content, substantially increasing yield. Compared with chemical fertilizer alone, 20% bio-organic fertilizer (N basis) increases soil nutrients, active organic matter by 11.9%, and yield by 6.6%. Fluorescence quantitative PCR shows that chicken manure compost increases ammonia-oxidizing bacteria and archaea abundance, improving N availability. Rice bran effectively reduces soil ferrous iron and increases rice yield, serving as a potential amendment, though whether organic manure promotes reductive substance formation or provides a "priming effect" requires further investigation.

3.3 Biological Measures

Screening gleyic-tolerant rice varieties provides an effective alternative where engineering measures are not feasible. Suitable varieties differ across regions due to varying climate and soil conditions. Generally, indica rice adapts better to cold-waterlogged environments than japonica and glutinous rice. Variety screening in Ningxiang, Taoyuan, and Yongxing counties in Hunan identified 'Luliangyou 996' and 'Lingliangyou 211' as superior early rice varieties, and 'Qianyou 1', 'Tianyou Huazhan', and 'Fengyuanyou 299' as superior late rice varieties. In gleyed paddy fields along the Jingjiang River, hybrid rice varieties such as 'Xiangzaoxian', 'Shanyou 63', and 'Weiyou 64', and rapeseed varieties 'Qinza 2' and 'Zhongyou 82' are considered adaptable. For variety evaluation, hydroponic experiments identified $120\ mg \cdot kg^{1}$ Fe^2 as the appropriate concentration for differentiating varietal tolerance, with plant height, root growth, root oxidation capacity, and dry matter yield proposed as identification indices. Li et al. proposed several gleyic tolerance indicators including root growth, root oxidation capacity during panicle initiation, tiller growth rate during early tillering, individual plant dry matter during late tillering, flag leaf catalase activity during milky stage, gleyic damage index, and photosynthetic intensity, identifying the hybrid variety ‘Weiyou 49’ as strongly gleyic-tolerant.

3.4 Alternative Utilization Approaches

Beyond traditional rice cultivation, site-specific utilization effectively enhances comprehensive productivity. Zhao et al. proposed utilization patterns for different gleyic degrees: for severely gleyed soils, returning fields to lakes and developing aquatic crops or ridge-fish culture; for moderately gleyed soils, shifting from traditional rice-rice to paddy-upland rotation. Rice-fish co-culture minimally affects physicochemical properties but significantly increases available nutrients, promotes rice growth, and increases yield.

China has over 115 million hectares of low-yield paddy soil. Increasing yield from 300–400 kg to 400–500 kg per 666.7 m^2 could add 10 billion kg of grain, significantly contributing to China’ s target of increasing grain production by 50 billion kg. Unlike other low-yield fields, cold-waterlogged paddy soils have high organic matter content and show greater fertilizer response and yield potential. Research on their improvement and utilization can efficiently use limited farmland resources, with profound significance for national food security, food quality safety, and ecological environmental security. Although government departments have increased efforts in farmland quality protection and improvement, most infrastructure projects focus on plain fields, with repeated construction in some plots while long-term investment in mountainous fields (including many cold-waterlogged fields) remains insufficient, resulting in low renovation standards and poor economic returns that affect farmer enthusiasm. Additionally, issues such as unclear land transfer and management, and insufficient technology integration for renovation and utilization patterns, contribute to the continued large area and abandonment of cold-waterlogged paddy fields in Jiangnan. Therefore, future renovation and utilization should be strengthened in the following areas:

1) **Basic and applied research**: First, investigate differences in soil structure and organic matter composition under various waterlogged states and dry-wet alternations to theoretically understand organic matter quality contributions to soil structure and aggregate formation. Second, strengthen research on methane emission characteristics in long-term waterlogged cold-waterlogged fields to enhance understanding of carbon cycling. Third, enhance ecological process studies of anaerobic microorganisms and associated enzymes during gleyization, including organic matter accumulation and transformation, nutrient decomposition and adsorption, and aggregate formation and destruction, to strengthen microbial regulation research for cold-waterlogged field improvement.

2) **Integrated technology models**: As understanding of cold-waterlogged field ecological functions deepens and ecological civilization construction advances, management should adopt a broad food security concept, combining agricultural structural adjustment and rational water resource uti-

lization to establish regionally appropriate integrated models. For different ecological types and production conditions, research should focus on: (a) Waterlogging control and high-yield efficient production models for lakeside low-lying cold-waterlogged fields with existing water infrastructure, integrating engineering measures, suitable varieties, rotation, balanced fertilization, and amendments to build high-standard farmland; (b) Green (organic) rice production models for hilly mountainous cold-waterlogged fields with poor infrastructure and drainage but superior natural environments, integrating simple ditching, suitable varieties, ecological control, P-K balance, and ridge cultivation for high-value rice and economic rotation; (c) High-value aquatic crop models for poorly drained cold-waterlogged fields with regional characteristics, developing lotus root, water bamboo, and rice-duck-fish or rice-fish systems with integrated fertilization, water, and pest management for economic and ecological benefits.

3) **Policy support**: Cold-waterlogged field management is a systematic project involving engineering, agricultural technology, policy, and management, requiring coordination among agriculture, comprehensive agricultural development, land, water resources, and management entities. First, governments should coordinate farmland infrastructure funds to include cold-waterlogged fields >7 hm^2 in national and local projects with higher subsidies than non-cold-waterlogged fields to maximize fund effectiveness. Second, introduce policies guiding enterprises, cooperatives, and large growers to transfer and lease cold-waterlogged fields for scaled management benefits. Third, establish special funds to integrate engineering with agronomic and biological technologies for synergistic improvement of comprehensive production and ecological functions. Fourth, develop renovation and utilization standards for different cold-waterlogged field types covering soil fertility, mechanization conditions, and ecological/socioeconomic benefits to provide evaluation criteria.

References

[1] Zeng X B, Zhang J B, Wei C F, et al. Status and reclamation strategy of low-yield fields in China[J]. Acta Pedologica Sinica, 2014, 51(4): 675–682

[2] Liu G R, Xu C X. Regulation Technology and Application of Cold-Waterlogged Field in Southern Yangtze River[M]. Beijing: Chinese Agriculture Press, 2014

[3] Luo T, Wang F. Survey Report of Characteristic of Cold-water Paddy Field and Engineering Improvement Utilization in Fujian[M]. Beijing: Chinese Agriculture Science and Technology Press, 2013

[4] Yang L, Zhao S J, Deng Y X, et al. Characteristics of waterlogging harm and ameliorative measures of cold waterlogged fields in hilly region of Hubei[J]. Hubei Agricultural Sciences, 1998(5): 24–27

[5] Xiong M B, Shu F, Song G Y, et al. Occurrence and ecological environmental construction of soil gleization in austral hilly area of China[J]. Soil and Environmental Sciences, 2002, 11(2): 197-201

[6] *An Introduction to China' s Agricultural Soil* Editorial Board. An Introduction to China' s Agricultural Soil[M]. Beijing: Chinese Agriculture Press, 1982

[7] Gong Z T, Zhang X P, Wei Q F. The formation, characterization and potential of Gleyic paddy soils in China[J]. Scientia Agricultura Sinica, 1990, 23(1): 45-53

[8] Lü H H, Liu Y X, Yang S M, et al. Classification comparison and improvement techniques of cold-waterlogged paddy in Southern District, China[J]. Acta Agriculturae Zhejiangensis, 2015, 27(5): 822-829

[9] Wang F, Li Q H, Lin Y Z, et al. Study on ground water level and microclimatic characteristics of cold-waterlogged paddy field[J]. Research of Agricultural Modernization, 2014, 35(3): 353-356

[10] Huang Z Q. The low-yield factors of cold-waterlogged paddy field[J]. Soil and Fertilizer, 1996(3): 13-15

[11] Soil Surveying Office in Fujian. Fujian Soil[M]. Fuzhou: Fujian Science and Technology Press, 1991

[12] Zhang Z Y, Tang W J, Xiong Y S, et al. Effects of amendment on aggregate stability of soil for cold waterlogged paddy field[J]. Journal of Huazhong Agricultural University, 2015, 34(4): 37-43

[13] Wang F, Li Q H, Lin C, et al. Establishing a minimum data set of soil quality assessment for cold-waterlogged paddy field in Fujian Province, China[J]. Chinese Journal of Applied Ecology, 2015, 26(5): 1461-1468

[14] Zhang M M, Xu X Y, Zhang Z Y, et al. Effects of land abandonment on soil aggregate and organic carbon stability in cold waterlogged paddy fields[J]. Chinese Journal of Eco-Agriculture, 2015, 23(5): 563-570

[15] Chai J J, Liao M, Xu P Z, et al. Feature analysis on nutrient' s restrictive factors of major low productive waterlogged paddy soil in China[J]. Journal of Soil and Water Conservation, 2012, 26(2): 284-288

[16] Chen N, Liao M, Zhang N, et al. Effects of exogenous ferrous on rice growth and soil microbial activities[J]. Journal of Plant Nutrition and Fertilizer, 2014, 20(3): 651-660

[17] Cai M Z, Lin X Y, Luo A C, et al. Effects of excessive Fe^2 on growth and physiological characters of rice[J]. Journal of Plant Nutrition and Fertilizer, 2002, 8(1): 96-99

[18] Cai M Z, Luo A C, Lin X Y, et al. Nutrient uptake and partitioning in rice plant under excessive Fe^2 stress[J]. Journal of Zhejiang Agricultural University:

Agriculture and Life Sciences, 2003, 29(3): 305-310

[19] Chen Z G, Xu C X, Zhu Q, et al. Effects of different types of cold water paddy field Fe^2 on physiological activity of rice[J]. Chinese Agricultural Science Bulletin, 2014, 30(12): 63-70

[20] He C M, Wang F, Zhong S J, et al. Dynamics of reductive organic acid and the relationship with growth of rice in cold-waterlogged paddy soil[J]. Fujian Journal of Agricultural Sciences, 2015, 30(4): 380-385

[21] Lin H B, Zhu Q, Chen Z G, et al. The toxic effects of hydrogen sulfate in waterlogged paddy field and improvement measures[J]. Tillage and Cultivation, 2014(5): 43-44

[22] Xie X M, Liao M, Zhang N, et al. EC50 of soil S^2 inhibiting rice growth and soil microbial activities[J]. Journal of Plant Nutrition and Fertilizer, 2015, 21(5): 1286-1293

[23] Lin Z Q, Xu P, Peng J G, et al. Study on types and amelioration of cold spring paddy soils[J]. Acta Pedologica Sinica, 1986, 23(2): 157-162

[24] Xiang W S, Li W H, Tong C L. Dynamic change of ground water level in waterlogged gleyed paddy soils in hilly red soil region and its effects on availability of soil nitrogen and phosphorus[J]. Acta Ecologica Sinica, 2002, 22(4): 513-519

[25] Zhang Y Z, Jiang Y L, Huang Y X, et al. Effects of rice-based cropping system, organic manure and groundwater level on phosphate sorption by paddy soils derived from red earth[J]. Acta Pedologica Sinica, 1998, 35(3): 328-337

[26] Xiang W S, Li W H, Tong C L. Studies on nutrients availability of S, Si, B and Cu in gleyed paddy soils derived from red earth[J]. Soil and Environmental Sciences, 2002, 11(1): 53-56

[27] Wang F, Li Q H, Lin C, et al. Active organic carbon and nitrogen in soils from typical cold-waterlogged paddy fields in Fujian[J]. Fujian Journal of Agricultural Sciences, 2014, 29(4): 373-377

[28] Lin Z Q, Chen J J, Zheng Z D. The characteristics of cold-waterlogged paddy field and improved way[J]. Fujian Agricultural Science and Technology, 1980(6): 4-6

[29] Qiu S L, Wang F, Li X Y, et al. Analysis of microbe and nutrient characteristics of cold-waterlogged paddy soil in Fujian Province[J]. Fujian Journal of Agricultural Sciences, 2012, 27(3): 278-282

[30] Lu X C, Xia G M. Studies on the activities of soil enzymes in gleyey rice soils[J]. Journal of Hunan Agricultural University: Natural Sciences, 1985(4): 25-31

[31] Deng S H, Ye C L, Liu T, et al. Distribution of soil nematodes in cold waterlogged paddy soil of southern region[J]. Soils, 2015, 47(3): 564-571

[32] Liu Z J, Zhou W, Li S T, et al. Assessing soil quality of gleyed paddy soils with different productivities in subtropical China[J]. CATENA, 2015, 133: 293-302

[33] Li D M, Yu X C, Liu K L, et al. Remediation effect of the combination of ditching drainage and agronomic managements on gleyed paddy field in Poyang Lake Region, China[J]. Journal of Plant Nutrition and Fertilizer, 2015, 21(3): 684-693

[34] Zhu H J. The problems digging into soil fertility potential of cold-waterlogged paddy field[J]. Scientia Agricultura Sinica, 1978(1): 73-77

[35] Wu X D, Dai Y S. The comprehensive improvement of cold-waterlogged paddy field in Chizhou, Anhui Region[J]. Soils, 1996(2): 62-63

[36] Chen S P, Dai H X. The effects of hidden drainage tubes on the reconstruction of cold-waterlogged paddy fields[J]. Journal of Zhejiang Agricultural Sciences, 2000(2): 59-60

[37] Lin C, Wang F, Li Q H, et al. Nutrient content and enzyme activity of cold-waterlogged soil in fields with open drainage ditches[J]. Fujian Journal of Agricultural Sciences, 2014, 29(10): 1010-1014

[38] Wang F, Lin C, Li Q H, et al. Effects of long-term drainage of stony open deep-narrow drainage ditches on groundwater level, soil chemical characteristics and rice grain quality in cold-waterlogged paddy fields[J]. Chinese Journal of Eco-Agriculture, 2015, 23(5): 571-578

[39] Qiu S L, Wang M K, Wang F, et al. Effects of open drainage ditch design on bacterial and fungal communities of cold waterlogged paddy soils[J]. Brazilian Journal of Microbiology, 2013, 44(3): 983-991

[40] Gu H H, Xiang W S, Li L. Study on the integral function of ditching to drain off excessive water in farming soil in wetland[J]. Journal of China Agricultural University, 1997(S1): 130-134

[41] Xiang W S, Li W H, Tong C L. Current status of waterlogging and soil gleyization of farm land in Jianghan Plain and the strategy for its management[J]. Soil and Environmental Sciences, 2000, 9(3): 214-217

[42] Xiang W S, Gu H H. The K fertilizer effect and influence on the oxidation reduction of gleying paddy field in low-lake region[J]. Soil and Fertilizer, 1997(2): 32-34

[43] Li Q H, Wang F, Lin C, et al. Effects of potassium fertilizer incensement on rice physiology and iron accumulation in cold-waterlogged paddy field[J]. Fujian Journal of Agricultural Sciences, 2015, 30(3): 243-248

[44] Xu X Y, Zhang M M, Liu Y, et al. Effects of regulating phosphorus and potassium supply on rice yield and nutrient absorption[J]. Journal of Plant Nutrition and Fertilizer, 2014, 20(5): 1076-1083

[45] Zhang X M, Guo X S, Wang W J, et al. Effects of different phosphorus sources and amount on rice yield and phosphorus use in cold-waterlogged paddy filed[J]. Journal of Anhui Agricultural Science, 2012, 40(34): 16604-16606

[46] Xu P Z, Xie K Z, Liu G R, et al. Effects of soil testing and formulated fertilization on rice yield and fertilization effect in cold waterlogged paddy field[J]. Guangdong Agricultural Sciences, 2012(22): 70-73

[47] Cai M Z, Luo A C, Lin X Y, et al. Effects of Ca^{2} on activities of antioxidant enzymes and lipid peroxidation in rice under excessive Fe^{2} stress[J]. Acta Agronomica Sinica, 2003, 29(3): 447-451

[48] Su J P, Fan F, Xie J, et al. Effect of middle and micro-elemental fertilizers supplement on rice yield in cold waterlogged paddy field[J]. Acta Agriculturae Jiangxi, 2013, 25(8): 25-29

[49] Wang S C, Cao C G, Li C F, et al. Effects of cultivation patterns on rice yield and soil properties in cold waterlogged paddy fields[J]. Chinese Journal of Eco-Agriculture, 2014, 22(10): 1165—1173

[50] Xu X Y, Zhang Z Y, Wang J, et al. Effect of ridging and fertilization on soil redox in cold waterlogged paddy fields[J]. Chinese Journal of Eco-Agriculture, 2013, 21(6): 666-673

[51] Xiong Y S, Xu X Y, Zhang Z Y, et al. Influences of combing ridge and no-tillage on rice yield and soil temperature and distribution of aggregate in cold waterlogged field[J]. Transactions of the CSAE, 2014, 30(15): 157-164

[52] Liu J, Luo Z C, Xiao X P, et al. Effects of different tillage and irrigation modes on reducing substances and rice growth of cold spring paddy soil[J]. Crop Research, 2014, 28(5): 466-469

[53] Xiang W S, Zhou W J, Gu H H. Effects of oxygen-releasing peroxides such as CaO on soil redox status and rice growth[J]. Acta Pedologica Sinica, 1996, 33(2): 220-224

[54] Zhao F, Wang D Y, Xu C M, et al. Response of morphological, physiological and yield characteristics of rice (Oryza sativa L.) to different oxygen-increasing patterns in rhizosphere[J]. Acta Agronomica Sinica, 2010, 36(2): 303-312

[55] Gu H H. Effects of rice-xerophyte rotation on amelioration of paddy soil[J]. Tropical and Subtropical Soil Science, 1995, 4(2): 78-84

[56] Wang F, Li Q H, Lin C, et al. Influence of paddy rice-upland crop rotation of cold-waterlogged paddy field on crops production and soil characteristics[J]. Chinese Journal of Applied Ecology, 2015, 26(5): 1469-1476

[57] Li Q H, Wang F, Lin C, et al. Effects of paddy-upland rotation on the nutrient activation of soil carbon nitrogen and phosphorus in cold waterlogged paddy field[J]. Journal of Soil and Water Conservation, 2015, 29(6): 113-117

[58] Wang W J, Zhang X M, Ling G H. Effects of biochar amendment on growth and yield of rice in cold water field[J]. Journal of Anhui Agricultural Sciences, 2013, 41(14): 6220-6221

[59] Zhang G, Li X K, Lu J W, et al. Effects of different measures on the concentration of reducing substances of soil and yield in cold waterlogged paddy field[J]. Chinese Agricultural Science Bulletin, 2014, 30(27): 153-157

[60] Sun G, Liu J, Luo Z C, et al. Effects of chemical fertilizers applied with biological organic fertilizer on soil nutrient and rice growth in cold-waterlogged paddy[J]. Hunan Agricultural Sciences, 2015(10): 44-46

[61] Xie K Z, Xu P Z, Yang S H, et al. Effects of supplementary composts on microbial communities and rice productivity in cold water paddy fields[J]. Journal of Microbiology and Biotechnology, 2015, 25(5): 569-578

[62] Cui H H, Chen Z G, Zhu Q, et al. Effects of different exogenous additives on ferrous iron content and rice yield in cold waterlogged paddy field[J]. Southwest China Journal of Agricultural Sciences, 2015, 28(1): 220-225

[63] Wang S C, Cao C G, Li C F, et al. Yield and physiology of middle-season rice in cold waterlogged paddy field at the southeastern of Hubei Province[J]. Hubei Agricultural Sciences, 2014, 53(16): 3736-3740

[64] Zeng Y, Huang M, Jiang P, et al. Studies on yield performance and high yielding cultivation methods of different types of cultivars in cold water paddy field[J]. Crop Research, 2010, 24(3): 140-144

[65] Zhao M Z, Deng Y J, Ma Y J. Studies on limiting factors in the productivity and ways for the utilization and amelioration of gleyed and swamped soils in the middle basin of the Yangtze River[J]. Resources and Environment in the Yangtze Valley, 1997, 6(1): 18-23

[66] Feng S H, Jia L H. Studies on rice Fe^2 -tolerance indexes with water culture[J]. Tropical and Subtropical Soil Science, 1996, 5(2): 80-84

[67] Li D M, Tang J J, Su Y R, et al. Appraisal of early rice tolerance to gleyic paddy soil in central and eastern Hunan[J]. Journal of Wuhan Botanical Research, 1992, 10(2): 139-151

[68] Zhou W. Theories and Approaches of Amelioration and Management of Low Yield Paddy Soils[M]. Beijing: Science Press, 2014

[69] Wang F, Li Q H, Lin C, et al. Responses to fertilization of rice on cold-waterlogged paddy fields developed from different landforms[J]. Fujian Journal of Agricultural Sciences, 2013, 28(8): 802-806