Postprint: Research Progress on Sink-Source Structure and Optimization and Regulation Patterns of High-Yielding Hybrid Mid-Season Indica Rice Varieties in Southern Rice Regions

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Abstract

Elucidating the source-sink structure of high-yielding rice varieties holds universal significance for guiding breeding practices. In large-scale rice production, determining high-yield, high-quality, and efficient cultivation models tailored to specific varieties—by leveraging their source-sink characteristics, key ecological and soil fertility indicators of the planting site, and their correlations with high-yield cultivation techniques—can not only save labor and financial resources required for variety-specific cultivation but also accelerate the demonstration and promotion of new varieties. Based on published literature combined with the author' s research findings over more than two decades, this study comprehensively analyzes research progress on the source-sink characteristics of high-yielding hybrid rice varieties and their variety-specific optimization and regulation patterns. The main contents include: (1) A spikelet number of 160-220 grains is optimal for high-yielding rice varieties, as these varieties not only reconcile the source-sink contradiction but also effectively utilize the photosynthetic capacity of basal green leaves; large-panicle types should appropriately increase grain fertilizer application to fully exploit the photosynthetic function of lower leaves, thereby improving seed setting rate and thousand-grain weight. (2) Adopting a high-yield cultivation strategy of expanding the 'sink' and increasing the 'source', nitrogen fertilizer application is increased to supplement the photosynthetic source, thereby ensuring satisfactory grain filling under high grain-leaf ratio conditions. The yield increase of dry-raised seedlings over local wet-raised seedlings exhibits a highly significant positive correlation with altitude and a highly significant negative correlation with the yield level of local wet-raised seedlings; the efficient nitrogen application rate for high-yielding rice demonstrates a highly significant linear relationship with geographical location and soil fertility. The yield-increasing effect of delayed nitrogen application shows a significant negative correlation with paddy field fertility, and increases yield by enhancing spikelet number and thousand-grain weight. A simple and practical new method was established to predict the efficient application rate of grain fertilizer (Y) using the SPAD value of flag leaves at full heading stage (X): Y= 30.798X+1 340.9, r=0.954 7**. A water management technique integrating high yield with water storage was developed. (3) The high-yield transplanting density of rice shows highly significant negative correlations with nitrogen application rate and spikelet number among different varieties; varieties with fewer spikelets per panicle are more suitable for intensive cultivation, and it is advisable to select small to medium panicle type varieties with spikelet numbers not exceeding 170 grains under conventional cultivation conditions. The relationship between yield increase from delayed nitrogen application (Y) and spikelet number of hybrid combinations (X) can be expressed as: Y=2 607.9 11.02X (R2=0.630 8), and spikelet number $ $237 grains can serve as a selection criterion for hybrid varieties suitable for the delayed nitrogen fertilization method. The main research areas requiring further supplementation and improvement include: the source-sink structure of hybrid rice varieties adapted to mechanical transplanting and harvesting, early seedling diagnosis and high-yield efficient fertilization techniques for hybrid rice, early monitoring and prevention techniques for lodging in hybrid rice, and efficient techniques for reducing nitrogen while increasing yield in hybrid rice.

Full Text

Preamble

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Research Progress on Sink-Source Structures and Optimal Regulation of High-Yield Varieties of Hybrid Mid-Season Indica Rice in Southern China

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Abstract: Understanding the sink-source structure of high-yield rice varieties holds universal significance for guiding breeding practices. In large-scale rice production, determining optimal high-yield, high-quality, and efficient cultivation models based on variety-specific sink-source characteristics combined with key ecological and soil fertility indicators can save substantial labor and

financial resources while accelerating the demonstration and promotion of new varieties. This paper synthesizes reported literature with over 20 years of research findings to comprehensively analyze research progress on sink-source characteristics and variety-specific optimization strategies for high-yield hybrid rice. Key findings include: (1) High-yield rice varieties with 160–220 grains per panicle optimally balance sink-source conflicts while effectively utilizing photosynthetic capacity of lower canopy leaves; large-panicle varieties require appropriate grain fertilizer application to maximize lower leaf photosynthetic function and improve seed-setting rate and 1000-grain weight. (2) A high-yield cultivation strategy of "expanding sink and increasing source" involves supplemental nitrogen application to maintain adequate grain filling under high grain-leaf ratios. Yield increases from dry-raised seedlings show extremely significant positive correlation with altitude and negative correlation with yield levels of wet-raised seedlings. Efficient nitrogen application rates show extremely significant linear relationships with geographic location and soil fertility. Yield benefits from postponed nitrogen application are significantly negatively correlated with soil fertility, increasing yield through higher panicle grain numbers and 1000-grain weight. A practical new method was established to predict efficient grain fertilizer rates (Y) based on flag leaf SPAD values at full heading (X): Y = -30.798X + 1340.9, r = 0.9547**. Water management techniques integrating high yield with water storage were developed. (3) Transplanting density shows extremely significant negative correlations with both nitrogen application rate and panicle grain numbers among varieties. Varieties with fewer panicle grains are more suitable for intensive cultivation; in production, small-to-medium panicle varieties with $ 170grainsperpanicleundertraditionalcultivationarerecommended.Therelationshipbetweenyieldincreasefr Y = 2607.9–11.02X(R^{2}$ = 0.6308), with $ $237 grains per panicle serving as a selection criterion for varieties suitable for postponed nitrogen fertilization. Future research should focus on sink-source structures for mechanized transplanting/harvesting varieties, early seedling diagnosis and high-yield fertilization techniques, early lodging monitoring and prevention, and nitrogen reduction with high-efficiency technologies.

Keywords: Hybrid rice; High-yield variety; Sink-source structure; Optimized control; Postponed nitrogen application; Nitrogen application rate; Grain number per panicle

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1. Theoretical Value of Rice Sink-Source Structure in Breeding and High-Yield Cultivation

Rice yield and grain quality represent integrated expressions of genotype-environment-management interactions, with genotype being the dominant factor for high yield and quality. In hybrid rice breeding, breeders select high-yield, high-quality varieties from hybrid offspring of genetically diverse parents. Different genotypes exhibit distinct phenotypic traits, and breeders conduct preliminary selection based on these sink-source characteristics. Due to varying ecological conditions and differing breeder perspectives on ideal plant types, diverse approaches have emerged in rice breeding. For instance, Huang Yaoxiang emphasized dwarf breeding in the 1960s[3], Yang Shouren proposed ideal plant type theory for super-high-yield rice in the 1980s[4], Zhou Kaida advocated heavy-panicle hybrid breeding in the late 20th century[5], Cheng Shihua proposed late-stage functional breeding in the early 21st century[6], while numerous other breeders maintain their own selection criteria. Despite these divergent approaches, all involve variety sink-source structures. Therefore, clarifying relationships between yield and sink-source structures provides universal guidance for breeding practice.

Regarding variety-specific high-yield and quality cultivation, initial research focused on developing cultivation techniques for individual varieties. Examples include Sun Yongjian et al.[7] studying water-fertilizer management effects on 'Gangyou 725' , Yang Zhiyuan et al.[8] and Xu Fuxian et al.[9] investigating cultivation methods and nitrogen management for 'IIyou 498' and 'Chuanyou 9838' , and recent work by the authors[9–10] exploring regional yield variations and efficient phosphorus-potassium application for high-quality hybrid rice 'Yuxiangyou 203' . However, with China' s vast rice cultivation area and hundreds of newly approved hybrid varieties annually, developing variety-specific cultivation techniques requiring 2–3 years per variety is impractical in terms of time, finances, and manpower. Consequently, research must focus on relationships between variety sink-source characteristics, ecological conditions, soil fertility, and high-yield cultivation techniques. This enables large-scale production to approximate optimal cultivation models based on variety sink-source traits and key ecological/soil indicators, saving substantial resources while accelerating new variety demonstration and promotion. Thus, variety-specific optimization research provides cost-effective, high-impact benefits.

2.1 Relationship Between Yield and Sink-Source Structure Among Varieties

Grain filling degree critically affects rice yield and is constrained by source-sink structure. Cao Xianzu et al.[11] classified mid-season indica and japonica varieties in the Yangtze River basin into three types: source-increasing, sink-increasing, and sink-source interaction types, with heavy-panicle varieties predominantly source-increasing and panicle-number types primarily sink-increasing[11–12]. Zhu Qingsen et al.[13] studied yield source-sink characteristics of numerous typical indica-japonica inter-subspecific hybrids, noting that while these combinations showed obvious sink capacity advantages, most exhibited inefficient photosynthate translocation to panicles, limiting yield potential. Inter-subspecific hybrid breeding could produce heavy-panicle combinations with >300 grains per panicle[14–15], but yield was often limited by insufficient "source" [11–13]. In heavy-panicle hybrid rice breeding, defining critical sink-source values provides selection criteria. Xu Fuxian et al.[16] investigated effects of source-sink structure on grain filling across multiple hybrid rice combinations under two density-fertility treatments. Results indicated that under high-yield conditions (theoretical yield $ $9 t/ha, potential yield $ $11 t/ha, seed-setting rate $ $80%), optimal panicle grain numbers were 160–220 grains, with corresponding ranges for effective panicles, 1000-grain weight, leaf-grain ratio, seed-setting rate, grain filling rate, grain filling index, and single panicle weight as shown in Table 1 , providing reference criteria for selecting high-yield hybrid combinations.

Analysis of these sink-source characteristics revealed that under large-scale high-yield cultivation conditions in the upper Yangtze River region, combinations with <160, 160–220, and >220 grains per panicle corresponded to sink-increasing, sink-source interaction, and source-increasing types, respectively. Sink-increasing types exhibited small sink-large source characteristics with good grain filling but underutilized source capacity. Source-increasing types showed the opposite pattern—large sink-small source with poor grain filling and unfulfilled yield potential. Sink-source interaction types represented the ideal balance. Therefore, production management should employ cultivation measures tailored to each type. Xu Fuxian et al.[17] further studied three winter paddy field types (summer drought, normal, and waterlogged fields), finding significant yield differences among 30 hybrid combinations across field types with consistent variation trends and non-significant variety × field type interactions. The primary high-yield target for winter paddy fields was increasing spikelet number through higher effective panicles, with specific sink-source characteristics identified for high-yield combinations across all three field types, consistent with previous results[16] (Table 1). Dwarf varieties possess physiological advantages including sturdy stems, dense nodes, low center of gravity, fertilizer tolerance, lodging resistance, strong tillering capacity, early and rapid tiller emergence, and high panicle formation rates[3]. Yuan Longping[15] noted that super-high-yield rice breeding lacks unified standards, with varying yield indicators proposed by different researchers, and presented phenotypic characteristics for super-high-yield hybrid rice based on specific varieties. Xu Fuxian et al.[18] studied relationships between sink-source characteristics during grain filling and yield across 15 hybrid mid-season rice varieties under high-yield cultivation, finding that high leaf area index (LAI) at heading and maturity stages and high aboveground dry matter weight formed the basis for high yield, with large sink and adequate source being key features. High-yield varieties (>9000 kg/ha) exhibited these characteristics: heading stage LAI of 6.5–7.0, maturity LAI of 3.5–4.0, biological yield of ~18,750 kg/ha, spikelet number >375 million/ha, and leaf-grain ratio of ~1.7 cm^2 per grain at heading.

Based on these findings, panicle grain number comprehensively reflects sink-source structure status, with 160–220 grains per panicle being optimal for high-yield varieties—preferably toward the upper limit in the upper Yangtze region and the lower limit in the middle-lower Yangtze region.

2.2.1 Role of Lower Canopy Leaves in Grain Filling and Relationship with Sink-Source Structure

Post-heading spikelet number determines yield potential, which is heavily constrained by grain filling performance. Wan Anliang et al.[19] investigated leaf-clipping effects on yield, finding no significant difference between treatments retaining the top three leaves versus all leaves, suggesting leaves below the 4th leaf contributed minimally to grain filling. This may relate to their use of small-panicle, high leaf-grain ratio conventional varieties. Our research using the medium-panicle hybrid 'Shanyou 63' showed that when the top three leaves (flag leaf, 2nd, and 3rd) maintained normal photosynthetic capacity, leaves below the 4th contributed little to yield[20], consistent with Wan et al.[19]. However, Yang Jianchang et al.[21] found that lengths of leaves 1–4 from the canopy top were extremely significantly correlated with total grains per panicle, while relationships between leaf length and seed-setting rate, 1000-grain weight, and individual plant yield varied substantially by variety type. For heavy-panicle hybrids like 'Shanyou 3', lengths of the 4th and 5th leaves showed significant positive correlations with yield, whereas for sink-limited varieties like 'Yanjing 2', these leaves had minimal impact. Ling Qihong et al.[22] suggested that lower leaves during early growth stages indirectly affect yield by influencing nutritional quality of subsequently developed leaves. Our further research[23] demonstrated that the contribution of leaves below the 4th leaf at heading stage depended on panicle grain number—varieties with >185 grains per panicle showed significant yield increases from these leaves, while those with <185 grains showed no effect. When panicle grain number exceeded 220, severe source limitation caused premature senescence and poor grain filling even with full utilization of lower leaves[16].

Selecting hybrids with 185–220 grains per panicle allows full exploitation of lower leaf photosynthetic function while maintaining high grain filling levels for high yield[24]. Synthesizing these results, lower leaf contributions during grain filling depend on variety type. Source-limited varieties should extend functional duration of leaves below the 4th leaf to promote grain filling, while sink-limited varieties require only normal utilization of the top three leaves.

2.2.2 Relationship Between Grain Weight Stability and Sink-Source Structure

Among yield components, 1000-grain weight is relatively stable but still varies considerably across ecological environments and cultivation levels. Wang Yulong et al.[25–26] analyzed grain traits in 'Wuyujing 2' at maturity, finding small differences in length and width but large variations in thickness and volume among grains of different specific gravities, with 1000-grain weight ranges up to 6.43 g. Across fertilizer treatments, 1000-grain weight ranges were 3.91 g for 'Shanyou 63', 5.43 g for 'Koganemasari', and 7.62 g for '9004'. Grains on lower primary branches showed greater weight increases than those on middle and upper branches, with consistent trends between primary and secondary branches[26]. Mechanisms underlying intra-variety grain weight differences were investigated from multiple perspectives including nitrogen timing/concentration, root activity, assimilate supply, filling process, and grain position[25–27].

Our research[28] using leaf-clipping, spikelet-thinning, and density-fertility treatments showed that inter-hybrid 1000-grain weight variation could reach up to 4.39 g, with greater variation in varieties having more panicle grains. For hybrids with $ 146grainsperpanicle, adequatesourcesupplyresultedin <
1gvariationacrosstreatments, servingasacriticalreferenceindicatorforvarietiesnotrequiringcultivationmea
sourceregulationeffectsonsuperiorandinferiorgrainsindicatedthatexcessivenitrogenapplicationhinderedg
grainweightthaninferiorgrains, butincreasingsourcesupplyandleaf −
grainratioenabledinferiorgrainstoachievefillinglevelscomparabletosuperiorgrainsundernormalconditions^

In summary, sink-source structure during grain filling substantially affects grain filling performance. Large-panicle varieties should receive appropriate grain fertilizer to maximize lower leaf photosynthetic function and improve seed-setting rate and 1000-grain weight.

2.3 Relationship Between Root Activity and Sink-Source Structure

Root function, particularly during middle and late growth stages, significantly impacts yield. Kawata et al.[30] reported that higher numbers of upper roots on the top three nodal root zones increased yield. Studies[31–32] showed that lower root numbers and absorption capacity below the 4th nodal position were significantly correlated with spikelet number, panicle weight, and yield, highlighting the importance of root vigor for high-yield breeding. However, direct field application remains challenging. Our research with 15 hybrid mid-season rice varieties revealed that strong root growth ability increased yield through higher effective panicles, while vigorous root activity improved seed-setting rate and showed extremely significant positive correlation with yield[33]. In field selection, strong tillering capacity and high seed-setting rate can serve as reference indicators for breeding varieties with vigorous root systems. Standardized genotypic values from 21 indica hybrid combinations were used in path analysis of 21 root and aboveground traits on seed-setting rate[34], showing that seven traits—tillers per plant at 4-leaf stage, tillers and dry weight per plant at peak tillering, root growth ability, LAI at heading, maximum tiller number, and panicle grain number—had significant or extremely significant partial correlation coefficients with seed-setting rate. High seed-setting rate varieties required strong tillering and root growth ability, high LAI at heading, and relatively small panicles.

Overall, small-to-medium panicle varieties with strong tillering and high seed-setting rate exhibit vigorous root activity and growth ability, favoring high yield.

3.1 High-Yield Cultivation Strategies

High-yield rice cultivation strategies must adapt to local conditions, showing clear regional differences. Zou Yingbin[35] proposed that super-high-yield cultivation should employ "stable early growth, attack middle stage, promote late stage" water-fertilizer management using medium-tillering, semi-dwarf, large-panicle varieties. Zheng Jiaguo et al.[36] noted that in Chengdu Plain' s rice-wheat/oil double-cropping areas, ensuring adequate effective panicles forms the yield foundation while increasing panicle grain number provides the key to higher yields. Our research indicates that high-yield strategies in Southwest China involve selecting lodging-resistant varieties, determining appropriate high-yield efficient nitrogen rates, emphasizing organic fertilizer application, and increasing soil available nitrogen, with primary targets of increasing effective panicles and seed-setting rate[37].

High rice yields require three conditions: (1) increasing optimal LAI to enhance photosynthetic "source" quantity and quality, primarily limited by local sunshine conditions[38]; (2) expanding "sink" capacity by coordinating panicle number and size; and (3) ensuring smooth "flow" of photosynthates to grains. Therefore, high-yield cultivation aims to maximize panicle grain number, seed-setting rate, and 1000-grain weight synchronously at elevated levels while maintaining high effective LAI and appropriate panicle numbers[39]. Specific measures include deep water irrigation or midseason drainage at peak tillering to control ineffective late tillers, improving panicle formation rate and coordinating panicle number-size conflicts[40–42]. This method works well in areas with reliable water supply but is difficult to implement in Southwest China' s winter paddy fields with poor irrigation infrastructure. Therefore, we proposed a sparse-planting, adequate-fertilization strategy for winter paddy fields[43], reducing peak tiller number through sparse planting to improve canopy light conditions, increasing panicle formation rate, moderately reducing effective panicles while substantially increasing panicle grain number, and expanding sink capacity under high-yield LAI conditions. Supplemental nitrogen application enhances photosynthetic source to ensure adequate grain filling under high grain-leaf ratios. The core technique involves 90,000 hills/ha and 210 kg N/ha (Table 2). Production practice demonstrates significant yield increases (Table 3), plus advantages of seed and labor savings, lodging resistance, reduced sheath blight incidence[44], and improved head rice rate with decreased chalky grain percentage[45].

3.2.1 Yield Increase Effect of Dry-Raised Seedlings and Relationship with Local Yield Level and Altitude

Robust seedlings form the foundation for high yield. Rice seedling methods 主要分为旱地育秧和湿润育秧两大类. Dry-raised seedlings feature early sowing, early transplanting, early maturity, high yield, and high efficiency[46–47], with yield benefits attributed to superior seedling quality and extended vegetative growth[48]. Our results show dry-raised seedlings do not increase yield universally. Yield increase over wet-raised seedlings shows extremely significant positive correlation with altitude and extremely significant negative correlation with wet-raised seedling yield levels[48] (Table 4), with significant benefits in areas below 6,750 kg/ha wet-raised yield or above 1,200 m altitude, but poor performance below 350 m altitude with wet-raised yields >9,750 kg/ha. The mechanism involves low-fertility fields in mid-low yield areas and high-altitude regions where wet-raised seedlings produce insufficient effective panicles, while dry-raised seedlings' stronger tillering substantially increases effective panicles. In low-altitude areas with higher fertility (possibly due to nutrient runoff from higher elevations), wet-raised yields are already relatively high. Although dry-raised seedlings increase effective panicles, reduced grains per panicle limit yield gains. In high-yield wet-raised areas with optimized panicle structure, dry-raised seedlings may increase effective panicles excessively, worsening canopy structure and causing panicle-grain conflicts that reduce yield gains or cause yield loss.

3.2.2 Relationship Between High-Yield Efficient Nitrogen Application and Geographic Location and Soil Fertility

Previous research extensively investigated efficient fertilizer utilization pathways. Zheng Shengxian et al.[49] proposed soil fertility improvement approaches based on nutrient status of high, medium, and low-yield paddy soils in Hunan' s double-cropping rice region. Zhang Xiuzhi et al.[50] developed an economic benefit function: $Y = -0.134X^2 + 37.097X + 12{,}533 - M$ ($R^2 = 0.9331$), where maximum economic benefit occurred at 138 kg N/ha, similar to SPAD-guided applications (140 kg N/ha). Yang Shaona et al.[51] found that applying 150 kg N/ha with organic fertilizer increased nitrogen physiological efficiency and recovery rate by 33.1 g/g and 50.6%, respectively, yielding 61.2% higher production. Wang Weini et al.[52] reported balanced N-P-K application increased yields by 57.4%, 44.0%, and 42.3% for early, mid, and late rice, respectively, with fertilizer contributions of 33.3%, 28.6%, and 27.8%, confirming balanced fertilization as key to yield improvement.

However, varying ecological conditions[53] and diverse soil fertility levels severely constrain application of previous findings. Our research[57] across seven ecological sites in four Southwest China provinces using uniform protocols established novel methods to determine efficient nitrogen rates based on geographic location and major soil nutrients (Table 5) with strong operability. Advantages include: (1) Using longitude, latitude, and altitude (closely related to climate) instead of climate data solves difficulties in obtaining meteorological information and can be precisely applied to specific fields with convenient, rapid data acquisition; (2) Requiring only selected soil nutrient indicators improves efficiency; (3) Establishing variety-specific nitrogen rate prediction models better reflects genotype responses to temperature, light, and fertilizers, providing stronger ecological adaptability.

3.2.3 Relationship Between Postponed Nitrogen Application and Soil Fertility Yield

Peng Shaobing et al.[54] argued that postponed nitrogen application improves nitrogen use efficiency by meeting substantial mid-late season dry matter accumulation requirements. Yang Zhiyuan et al.[8] reported that under 150 kg N/ha in intensive cultivation, panicle fertilizer accounting for 30% of total nitrogen achieved high yield with significantly improved nitrogen agronomic and physiological efficiency. Sun Yongjian et al.[55] found that under 180 kg N/ha, optimal postponed nitrogen proportion was 40–60% for flooded irrigation and 20–40% for dry cultivation. Du Xiaodong et al.[56] recommended a base:tiller:panicle:grain fertilizer ratio of 5:3:1:1. Huo Zhongyang et al.[57] advocated a 5:5 early-mid season nitrogen split. However, some studies found no yield benefit from nitrogen postponement. Li Wu et al.[58] reported panicle nitrogen increased yield for 'Peizataifeng' but not 'Huayou 86' . Xu Fuxian et al.[59] found the base:tiller = 7:3 treatment yielded highest, with 20–30% nitrogen postponement showing no significant benefit. Qiu Shaojun et al.[60] observed no significant effects on biomass, grain yield, nitrogen use efficiency, or yield components compared to farmer practice.

These single-location studies raise questions about whether differences relate to varying soil fertility levels. Our research[60] across seven Southwest China ecological sites over two years found that nitrogen rate and postponement proportion effects varied by site depending on soil fertility. In high-fertility fields (blank yield >7,000 kg/ha), postponed nitrogen showed poor yield benefits. Yield-increasing postponed nitrogen treatments featured moderate nitrogen rates and small postponement proportions, increasing yield through higher panicle grain number and 1000-grain weight while maintaining adequate effective panicles. This demonstrates that field fertility differences significantly affect postponed nitrogen efficacy—medium-low fertility or poor water/nutrient retention fields suit postponed nitrogen, while high-fertility fields maintain adequate mid-season fertility even with reduced early nitrogen, making additional nitrogen application ineffective and wasteful. Therefore, high-fertility fields should reduce total nitrogen and postponement proportion, using plant-based diagnostics to determine postponement amounts.

3.2.4 Relationship Between Efficient Grain Fertilizer Application and Flag Leaf SPAD Value

Regarding panicle-grain fertilizer effects, Feng Weizhu et al.[61] found panicle fertilizer affected soil nitrogen supply through heading-maturity, while grain fertilizer only affected heading-maturity nitrogen uptake. Increased grain fertilizer improved tiller survival and promoted large panicles. Tao Shishun et al.[62] reported grain fertilizer slowed leaf senescence in large-panicle hybrids and increased yield through higher seed-setting rates. Yang Lianxin et al.[27] found excessive grain fertilizer reduced grain filling. These qualitative studies insufficiently meet production quantification needs. We therefore developed a quantitative relationship between flag leaf SPAD value at heading (X) and efficient grain nitrogen rate (Y, kg/ha): Y = -30.798X + 1340.9 (R^2 = 0.9114)[63]. This method solves quantitative grain fertilizer application, improves nitrogen efficiency, and provides a scientific, simple prediction approach.

In summary, nitrogen postponement efficacy depends on soil nitrogen supply and plant nutritional status. When these adequately support late-season growth, postponed nitrogen provides no benefit, making plant-based diagnostics crucial for determining appropriate postponement amounts.

3.2.5 Effect of Water Management on Grain Yield

Based on this theory, Ling Qihong et al.[40] and Jiang Pengyan et al.[41] proposed deep water irrigation or midseason drainage when total tiller number reaches ~80% of target panicle number, achieving 90–95% panicle formation rates, promoting large panicles, and resolving panicle number-size conflicts to expand sink capacity[42]. However, this method is difficult to apply in southeastern Sichuan' s winter paddy fields due to poor irrigation infrastructure and technical requirements: water depth must not submerge the collar of the uppermost fully expanded leaf on main stems, gradually deepening as plants grow until 50% of main stems show the second leaf from top, requiring 10–15 days of deep water during high temperature-humidity conditions that induce severe sheath blight. Alternative midseason drainage requires 40–50% soil relative water content (firm soil, footprint without sinking), repeated shallow irrigation and drainage cycles until 50% of main stems show the second leaf from top, also requiring reliable water supply that is often unavailable during frequent spring-summer droughts. We therefore invented a "water management technology integrating high yield with water storage in winter (fallow) paddy fields" (patent pending): 0–6 cm water layer from transplanting to peak tillering and booting-maturity stages, 0–20 cm from peak tillering to booting stage, and 0–35 cm from harvest to next transplanting. Compared to traditional methods, this significantly increases yield across panicle types while utilizing natural precipitation and enhancing drought resistance.

3.3.1 High-Yield Suitable Transplanting Density and Panicle Grain Number Among Varieties

Previous variety-specific cultivation research was extensive[6–10], but studies on universal high-yield techniques across varieties were rare. Analyzing our team' s 1978–1996 high-yield cultivation data for 25 early and mid-season rice varieties revealed extremely significant differences in optimal transplanting density and effective panicle number among varieties[64]. High-yield hill number (Y, $\times 10^{4}$/ha) showed extremely significant negative correlations with panicle grain number (X_1) and nitrogen
$Y = 61.545 - 0.1749X_{1} - 0.06681X_2$ (F = 160.76**, N = 19), while other cultivation techniques showed no significant differences. Therefore, in large-

scale production, knowing only variety panicle grain number and field nitrogen rate can determine optimal transplanting density, with sowing date, rate, transplanting leaf age, and hills per hole following local conventional practices, eliminating the need for variety-specific cultivation research.

Expanding sink capacity to increase grain-leaf ratio under high-yield LAI conditions improves photosynthetic efficiency and yield[39].

3.3.2 Adaptability of Hybrid Rice Varieties to Intensive Cultivation

Since 2000, rice intensive cultivation systems have been widely researched and demonstrated in southern China with controversial yield effects. Xu Fuxian et al.[44] found that in medium-high fertility winter paddy fields under intensive cultivation (3.5-leaf transplanting, 195 kg N/ha), both excessively sparse (48,300 hills/ha) and dense (189,100–216,400 hills/ha) densities yielded significantly less than current high-yield practices (4.5-leaf transplanting, 228,700 hills/ha, 150 kg N/ha). However, densities of 75,100–148,000 hills/ha achieved or exceeded current high-yield levels. Zhong Haiming et al.[65] reported significant yield and economic benefits from intensive cultivation, recommending $ 75,000*hills/ha.XuFengyingetal.*^{66}$ found intensive cultivation delayed root and leaf senescence, improving seed-setting rate and 1000-grain weight. Ma Jun et al.[67] tested 12 hybrid combinations in Mianyang and Wenjiang, Sichuan, finding 75,000 hills/ha produced higher yields through substantially increased effective panicles. However, IRRI and others reported that original intensive cultivation technology causes significant yield losses in large-scale production, requiring localization (reported at National Crop Cultivation Academic Conference, Sanya, April 2003).

Intensive cultivation' s core techniques are sparse planting and young seedlings, with variable yield effects likely related to tested varieties. Regarding variety adaptability, Ma Jun et al.[67] noted that intensive cultivation enables full tillering potential (70–80 tillers per plant at 45,000 hills/ha), recommending medium-large panicle varieties with medium-high tillering capacity. Zhong Haiming et al.[65] suggested medium-high tillering, slightly loose plant types at $ $75,000 hills/ha. Our research with 18 hybrid mid-season combinations showed extremely significant negative correlation between yield differences (intensive vs. traditional cultivation) and panicle grain number—varieties with $ 170*grainsperpanicleundertraditionalcultivationshowedsignificantyieldincreaseswithintensivecultivation*
170*grainsshowedequalorreducedyields*^{68}$.

The mechanism involves low-panicle-grain varieties achieving substantial panicle grain increases under intensive cultivation despite reduced effective panicles, maintaining stable seed-setting rate and 1000-grain weight for overall yield increase. Conversely, large-panicle varieties with weaker tillering capacity show significant effective panicle reductions and seed-setting rate declines due to intensified sink-source conflicts, making panicle grain increases insufficient to compensate for losses.

We conclude that original intensive cultivation technology must be innovated according to China' s production and ecological conditions for effective yield and income gains. Key techniques include: strong-tillering varieties, young seedling transplanting, varieties with $ $170 grains per panicle under traditional cultivation, optimal density of 75,000–150,000 hills/ha (maximum 180,000 hills/ha).

3.3.3 Sink-Source Characteristics of Varieties Adapted to Different Cultivation Modes

Many researchers have studied plant morphological characteristics of high-yield varieties in different regions. Du Yong et al.[69] proposed high-yield plant type features for different japonica varieties in the Huang-Huai region. Zeng Yongjun et al.[70] preliminarily studied high-yield plant type characteristics for double-cropping rice in the middle-lower Yangtze region. Yang Jianchang et al.[71] identified yield and plant type evolution trends in mid-season indica rice. Zhou Kaida et al.[72] considered inter-subspecific hybrid breeding an important pathway for super-high-yield varieties and proposed breeding strategies and variety characteristics. These findings importantly guide regional high-yield breeding.

High rice yield results from genotype-ecology-technology interactions, requiring different variety types for different regions and cultivation modes. Xu Fuxian et al.[64] analyzed relationships between high-yield cultivation techniques and plant morphological characteristics of 25 early and mid-season varieties, finding significant negative correlation between plant type looseness and optimal cultivation density. Winter paddy fields suit panicle-number types with young seedling sparse planting and adequate fertilization[44]. Further analysis showed average yields across 20 hybrid mid-season varieties under three cultivation modes ranked: high-density low-fertilizer > medium-density medium-fertilizer > low-density high-fertilizer, with varieties selected for each mode and universal varieties identified, using seed-setting rate as the scientific basis for mode adaptability[73].

Overall, different ecological regions require different sink-source characteristics, and within the same region, different cultivation modes require adapted variety types. Production practice should match appropriate cultivation modes and variety types to specific ecological conditions to improve promotion efficiency of new varieties and technologies.

3.3.4 Sink-Source Characteristics of Varieties Adapted to Postponed Nitrogen Application

Previous studies showed inconsistent yield effects from postponed nitrogen application[8],[55–56],[58–59], possibly related to tested varieties. Using 20 hybrid mid-season combinations, we compared "postponed nitrogen (base:panicle initiation:spikelet protection = 6:2:2)" versus "heavy base-early tiller (base:tiller =

7:3)" fertilization methods. Yield differences between methods (Y) and panicle grain number (X) followed: Y = 2607.9 -11.02X (R^2 = 0.6308)[74]. Accordingly, varieties with $ $237 grains per panicle suit postponed nitrogen application, while those with >237 grains show yield reduction. Low-panicle-grain combinations with strong tillering maintain adequate effective panicles despite reduced early nitrogen and peak tiller number, achieving higher panicle grain number and seed-setting rate for significant yield increases. Conversely, large-panicle varieties with weak tillering suffer excessive peak tiller and effective panicle reductions, causing yield loss.

In conclusion, postponed nitrogen efficacy depends on both variety type and soil fertility. Generally, strong-tillering varieties on medium-high fertility soils respond well to postponed nitrogen. For large-panicle varieties, total nitrogen should be moderately increased with postponed nitrogen proportion limited to 20–30%.

3.3.5 High-Yield Cultivation Techniques for Mechanical Transplanting

Recent progress in mechanical transplanting research has been rapid in southern China[75]. Zhang Hongcheng et al.[76] proposed key precise quantitative techniques: "standardized seedlings, precise transplanting, steady growth, early drainage, optimized middle stage, strengthened late stage." Su Boyuan et al.[77] developed cultivation techniques for super rice 'Yongyou 12' to achieve 15,000 kg/ha with yield components: 2.19 million panicles/ha, 329 grains/panicle, 86% seed-setting rate, and 25.5 g 1000-grain weight. Our research[78] on multiple hybrid mid-season combinations in winter paddy fields showed mechanical transplanting extended grain filling by average 1.9 days compared to hand transplanting, with higher maximum tillers, effective panicles, and seed-setting rate but lower panicle grain number and 1000-grain weight, yielding 184.5 kg/ha (2.54%) more. Maximum tiller number showed significant negative correlation with yield increase, suggesting medium-high tillering varieties suit mechanical transplanting. High-yield techniques include: 80 g seed per tray, 90–135 kg N/ha with traditional heavy base-early tiller split, transplanting at 4.5-leaf stage with 29.7 cm × 19.8 cm spacing.

Seedling quality substantially affects mechanical transplanting yields. Developing environmentally friendly seedling trays using rice straw instead of plastic trays enables effective straw return and sustainable development[79]. Chen Huizhe et al.[80] designed such straw trays, showing robust seedling growth with roots penetrating tray bottoms, good mat formation without breakage during handling, and yields comparable to plastic trays, providing a viable alternative.

4. Research Prospects for High-Yield and High-Efficiency Theory and Technology of Hybrid Rice

In summary, China has made major progress in sink-source structures and variety-specific high-yield cultivation regulation technologies for hybrid rice. Applying current findings, basic high-yield cultivation protocols can be developed for hybrid varieties given their growth duration, key sink-source characteristics, and target region' s geographic location and soil fertility, including seedling methods, transplanting density, cultivation mode, and nitrogen management. However, diverse soil types, fertility levels, and inter-annual climate variations limit precise technology development, requiring further research.

4.1 Sink-Source Structure Research on Hybrid Rice Varieties Adapted to Mechanical Transplanting and Harvesting

With China' s economic restructuring and rural labor shortages, rice production scaling and mechanization are accelerating. Mechanization includes mechanical transplanting, harvesting, and drying. While high-yield agronomy for mechanical transplanting has achieved notable success[75], limited literature addresses sink-source characteristics for varieties suited to mechanical transplanting and harvesting. Our comparative trials of 10 hybrid mid-season combinations showed average 2.54% yield increase with mechanical transplanting, with 6 varieties gaining and 4 losing yield, and significant negative correlation between maximum tiller number and yield increase, indicating variety-specific suitability. Additionally, mechanical harvesting causes substantial grain loss, with plant maturity posture, canopy leaf status, and soil hardness affecting efficiency[81]. Urgent research is needed on sink-source characteristics for mechanical transplanting/harvesting varieties and optimal drainage timing and machinery selection for different paddy field types.

4.2 Early Seedling Diagnosis and High-Yield Efficient Fertilization Techniques for Hybrid Rice

Despite systematic research on high-yield efficient technical models—such as precise quantitative cultivation theory[82], intensive cultivation[83], and super rice "three-determination" cultivation[84]—these technologies often fail to achieve expected yields in large-scale production due to inadequate implementation, particularly insufficient transplanting density or nitrogen rates. Mid-late season panicle or grain fertilizer applications provide some compensation but cannot fundamentally overcome inadequate density[8],[10],[61]. Such fields require early seedling diagnosis and prompt nitrogen application to increase effective panicles, yet research in this area is scarce. Guo Xiaoyi et al.[85] found that at 12 days after transplanting, any leaf position from main stems or tillers could be sampled, with top 1st and 3rd leaves at maximum tillering being most sensitive for SPAD-based diagnosis of early field nitrogen supply capacity. Further research should combine tiller numbers with SPAD values to develop relationships with high-yield efficient nitrogen rates for early diagnosis and fertilization.

4.3 Early Monitoring and Prevention Techniques for Lodging in Hybrid Rice

High yields are often accompanied by lodging risks from variety susceptibility, excessive density, early over-fertilization, and late-season storms. Previous lodging research focused on morphological characteristics at lodging occurrence, cultivation-lodging relationships, and post-lodging loss reduction, with minimal investigation of early monitoring and prevention[86]. Research should be strengthened on relationships between early growth stage (30–50 days after transplanting) nitrogen content, seedling dynamics, and tiller numbers with late-season (heading-maturity) lodging severity, plus effects of early agronomic measures and plant growth regulators on lodging mitigation to achieve both high yield and lodging resistance.

4.4 Research on Nitrogen Reduction with High-Efficiency Techniques for Hybrid Rice

Recent breakthroughs in super rice breeding and super-high-yield cultivation have produced numerous high-yield examples, crucial for national food security. However, these demonstrations rely heavily on high fertilizer inputs, particularly nitrogen, causing problems of high yield without income increase, low fertilizer use efficiency, and water eutrophication from nutrient runoff, threatening agricultural sustainability. Urgent research is needed on nitrogen reduction with high-efficiency techniques, focusing on multi-year location studies of nitrogen reduction effects on yield and marginal benefits across different soil fertility levels to develop cultivation systems achieving nitrogen reduction, yield increase, high efficiency, and sustainability in different ecological regions.

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