

RECENT ADVANCES IN DIRECT SEEDED RICE: PHYSIOLOGICAL ADAPTATION, CROP MANAGEMENT, AND GENETIC IMPROVEMENT

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ABSTRACT

Owing to insufficient water, labour shortages and accelerating climate change, direct seeded rice (DSR) has emerged as a feasible and resource-efficient alternative to conventional transplanted puddled rice (TPR) systems, conserving water and reducing methane emissions. However, the initial growth phases are frequently impeded by inadequate seedling emergence, intensive weed competition, nutritional deficiencies and exposure to variable soil moisture and aeration conditions in some DSR systems, including low nitrogen use efficiency, which can impair the establishment of a healthy crop stand and stability of its yield under DSR. Identifying and phenotyping rice germplasm for critical physiological traits is essential for developing cultivars that thrive in DSR environments. The physiological basis of genotypes adaption to DSR conditions need to be integrated with phenotyping and breeding strategies. This review synthesizes the knowledge of the physiological traits that facilitate DSR adaptation evaluates both conventional and high-throughput phenotyping (HTP) techniques — digital imaging, canopy temperature measurement, chlorophyll fluorescence analysis, and remote sensing technologies to precisely evaluate these traits in field and controlled environment and examines how quantitative trait loci (QTL) mapping, genome-wide association studies (GWAS), and marker-assisted selection (MAS), significantly facilitates the development of rice varieties suitable for DSR. The review highlights the importance of multi-trait phenotyping frameworks and multi-environment testing in accelerating genetic improvement and ensuring sustainable rice production in direct seeded agricultural systems.

KEYWORDS: Direct seeded rice; early seedling vigour; phenotyping; physiological traits; genetic improvement

1.INTRODUCTION:

Rice (*Oryza sativa* L.) is a fundamental staple food globally, providing calories and livelihoods to billions of individuals, predominantly in Asia and Africa. Conventional transplanted puddled rice (TPR) involves nursery raising followed by transplanting into puddled and generally flooded fields. Although this system provides reliable crop establishment, it involves huge amount of water, energy and labour inputs. Increasing water scarcity and labour shortages have increased the interest in direct seeded rice (DSR) as a resource efficient alternative to transplanted rice system cultivation. (Sandhu et al., 2021; Van Hung et al., 2024; Farooq et al., 2011)

Direct seeded rice (DSR) refers to rice establishment by sowing seed directly into the field, without nursery raising and transplanting. DSR includes dry direct seeded rice (DDSR), in which dry seed is sown into non-puddled, relatively dry soil; wet direct seeded rice (WDSR), in which pre-germinated seed is sown on wet or puddled soil; and water seeding, in which seed is broadcast or sown into standing water. Therefore, soil moisture and aeration conditions in DSR vary according to the establishment method and subsequent water management, and DSR should not be considered synonymous with aerobic rice. This technique conserves total irrigation water, reduces methane (CH₄) emissions under alternate wetting and drying (AWD) management, and decreases labor costs by avoiding puddling and transplanting (Farooq et al., 2011; Xu et al., 2019; Chakraborty et al., 2017). DSR thus aligns more effectively with the objectives of mechanization and climate-smart agriculture.

Despite these advantages, DSR exposes rice plants to an array of early environmental challenges. In aerobic soils, weed seeds germinate simultaneously with rice, creating intense competition for light, nutrients, and moisture throughout the critical establishment phase. Soil crusting, temperature fluctuations, inconsistent soil moisture, and the risk of transient flooding or waterlogging immediately post-sowing further jeopardize seedling establishment (Farooq et al., 2011; Shekhawat et al., 2020). Aerobic soil conditions also alter nitrogen dynamics favoring nitrification-denitrification cycles over the stable ammonium (NH₄⁺) environment of flooded TPR and increasing the risk of micronutrient deficiencies, particularly zinc (Zn) and iron (Fe) (Negi et al., 2024; Kumar and Ladha, 2011; Sagare et al., 2020).

The capacity of rice genotypes to acclimatize to DSR is predominantly determined by their physiological and morphological attributes. These include early seedling vigour (ESV), rapid coleoptile or mesocotyl elongation, anaerobic germination (AG) tolerance, deep root system architecture (RSA), efficient nitrogen and micronutrient absorption, and resilience to abiotic stressors such as drought and oxidative stress. Significant genotypic variation exists for all of these traits, providing plant breeding programs with the opportunity to select and develop DSR-

adapted cultivars through systematic phenotyping and genomic approaches (Bista, 2018; Anandan et al., 2020; Mahender et al., 2015; Singh et al., 2024; Kumar et al., 2022a).

Recent research has increasingly focused on high-throughput phenotyping (HTP) to precisely quantify adaptive traits across large germplasm panels. Digital phenotyping methods, non-destructive imaging, and remote sensing provide rapid measurement of seedling growth rates, biomass accumulation, canopy structure, root architecture, and drought responses. Concurrently, genetic investigations including QTL mapping and GWAS have identified genomic regions associated with traits that facilitate DSR adaptation (Verma and Sandhu, 2024; Gong et al., 2024). Therefore, this review examines the physiological traits associated with DSR adaption, evaluates conventional and high-throughput approaches for their phenotyping and discusses how physiological approaches can be integrated with modern breeding strategies to develop resource-efficient DSR cultivars

2. Merits of Direct Seeded Rice:

The method of crop establishment in DSR significantly differs from that of TPR in ways that confer multiple agronomic, environmental, and economic advantages. DSR conserves 15–35% of total irrigation water by eliminating puddling and reducing submergence duration, with water requirements of 900–1,200 mm/season compared with 1,200–2,000 mm/season for TPR (Xu et al., 2019; Chakraborty et al., 2017; Tuong et al., 2002). Labor requirements are substantially lower, 30–50 man-days/ha in DSR versus 60–120 man-days/ha in TPR because the nursery raising, puddling, and manual transplanting operations are all eliminated (Sandhu et al., 2021; Farooq et al., 2011).

The absence of puddling in DSR allows rice plants to develop deeper and broader root systems in the unpuddled aerobic soil, as summarized in Fig. 1. Root penetration depths of >60 cm have been documented in DSR, compared with <30 cm in TPR systems where puddling induces anaerobic conditions and mechanical impedance (Panda et al., 2021; Sangeetha et al., 2024). This deeper RSA enhances the capacity to absorb water and nutrients under dry conditions, constituting a critical physiological advantage for yield stability under water-limited scenarios. (Fig 1)

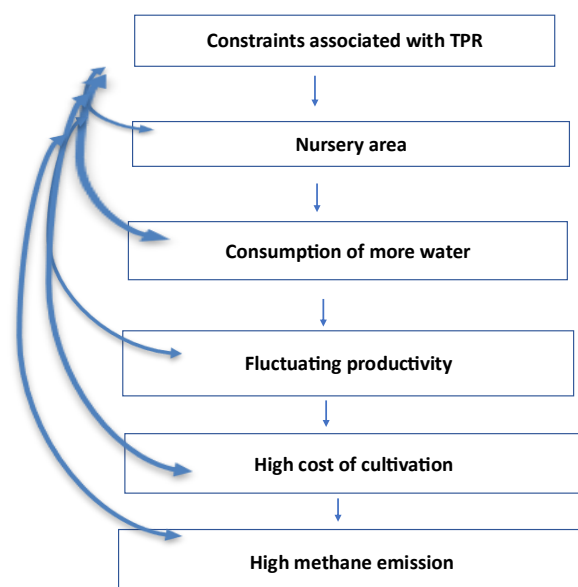


Fig 1. Constraints in conventional transplanted rice

The schematic illustrates the major limitations associated with conventional transplanted rice (TPR) cultivation systems. Continuous reliance on this method contributes to deteriorating soil health and depletion of groundwater resources due to excessive water requirements. Labor scarcity and high cultivation costs further increase the economic burden on farmers. Conventional transplanting also results in low plant density and higher methane emissions under flooded conditions. Collectively, these constraints lead to reduced productivity and raise concerns regarding the sustainability of rice production systems.

From an environmental perspective, the aerobic or intermittently moist soil conditions in DSR markedly reduce the activity of methanogenic microorganisms. Research employing soaking-and-drying cycles demonstrates that DSR systems can reduce CH₄ emissions, representing a major contribution to climate change mitigation (Liu et al., 2022; Chaudhary et al., 2025; Kaur and Singh, 2017). Crop duration is also typically 7–10 days shorter in DSR, facilitating more flexible crop rotations and reducing exposure to terminal drought at grain filling. Direct seeded rice and transplanted rice with respect to agronomic performance, physiological characteristics, resource-use efficiency, crop establishment methods, weed dynamics, water and nutrient management, labor requirements, and environmental implications are given below (Table 1).

Table 1. Comparative overview of direct -seeded rice (DSR) and transplanted rice (TPR)

Aspect	Direct Seeded Rice (DSR)	Transplanted Rice (TPR)	Reference
Crop establishment	Seeds are directly sown in the dry and wet lands	Raising seedlings in nursery followed by transplanting	(Farooq et al., 2011; Kumar and Ladha, 2011)
Water requirement (mm/season)	Generally lower, savings include 11-14% in wet-DSR in the Philippines	Generally higher	(Kumar and Ladha, 2011)
Labour (man-days/ha)	11-66% lower labor requirement	Generally higher	(Kumar and Ladha, 2011)
Weed pressure	High; aerobic soil allows diverse grass, sedge, and broadleaf species	Low	(Shekhawat et al., 2020; Negi et al., 2024)
Root development	Root development varies with soil, moisture and genotype	Puddling modifies root development	(Panda et al., 2021; Sangeetha et al., 2024)
Soil environment	Variable moisture and aeration	Flooded conditions.	(Negi et al., 2024; Kumar and Ladha, 2011)
CH ₄ emissions (kg CH ₄ /ha/season)	Lower; 3–12 kg CH ₄ /ha/season; AWD further reduces by 47–96%	High; 20–100 kg CH ₄ /ha/season due to prolonged anaerobic soil conditions	(Liu et al., 2022a; Chaudhary et al., 2025; Kaur and Singh, 2017)
Crop duration (days)	Often 7–10 days earlier maturity	Depends on transplanting date and genotype	(Farooq et al., 2011; Kaur and Singh, 2017)
Nutrient use efficiency (NUE, kg grain/kg N)	Strongly affected by genotype and N management; 16kg grain/kg N agronomic efficiency and 43.56 kg grain/kg N partial factor productivity were reported under dry DSR	Higher NUE under flooded conditions physiological N use efficiency of 42-43 kg grain/kg N was reported in one comparative study	(Subedi et al., 2018; Chen et al., 2014)

DSR=direct seeded rice; AWD = alternate wetting and drying; NUE = nitrogen use efficiency; GHG = greenhouse gas.

3. Constraints in Direct Seeded Rice

Despite its potential, DSR yields are frequently constrained by the interplay of biotic and abiotic stresses that are more pronounced under the variable soil moisture and aeration conditions that characterize different DSR systems compared with flooded TPR (Su et al., 2022); the major constraints are summarized in Fig. 2. Understanding the physiological basis of these limitations is essential for designing effective phenotyping and breeding strategies.

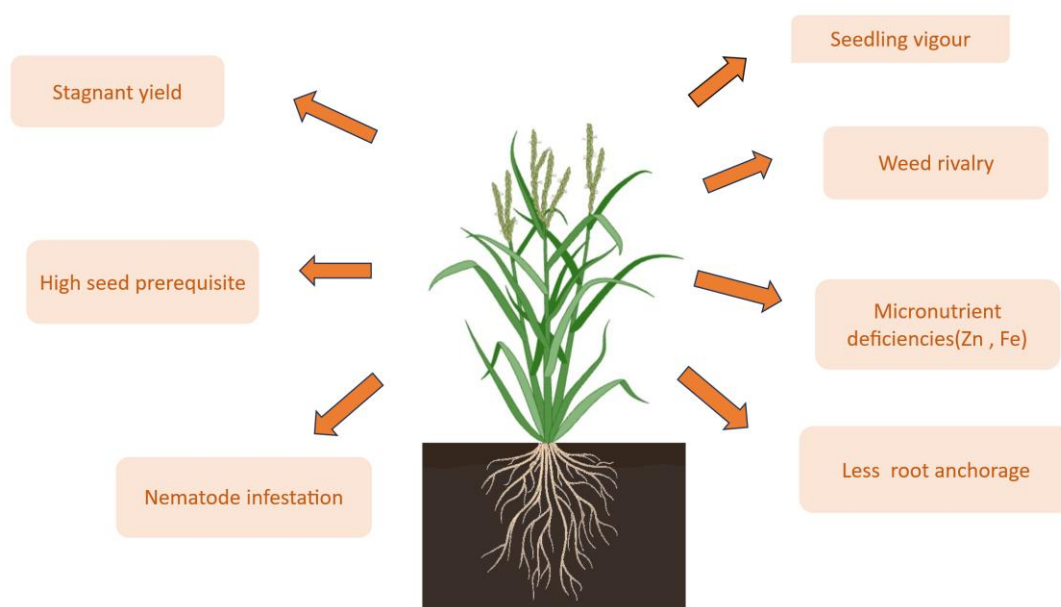


Fig 2. Schematic diagram of constraints associated with DSR

This schematic illustrates the agricultural constraints and physiological vulnerabilities that severely limit crop production and resource optimization. Above ground, the diagram highlights critical challenges including stagnant yields, high seed requirements, intensified weed rivalry. Below the surface, subterranean stress is depicted through micronutrient deficiencies that impair metabolism and plant vigour. Ultimately, these combined biological and environmental pressures culminate in poor root architecture, resulting in weak anchorage.

3.1 Poor and Non-Uniform Crop Establishment

In DSR, seeds must germinate and emerge through the soil surface without the benefit of nursery management or the moderating influence of standing water on soil moisture and temperature. Surface-sown seeds are vulnerable to predation (birds, rodents), mechanical damage from raindrop impact, and desiccation from surface soil drying. Temperature fluctuations during the seedling emergence phase, particularly high soil surface temperatures ($>35^{\circ}\text{C}$) under tropical conditions, can reduce membrane integrity, impair amylase activity, and reduce α -amylase-mediated starch mobilization in the germinating seed, thereby depressing germination percentage and seedling vigour index (SVI) (Fahad et al., 2017; Dey et al., 2026; Sakhale, 2022). Laser land levelling to ± 2 cm precision and precision seeders that ensure consistent sowing depth (2–3 cm) are critical agronomic interventions to improve establishment uniformity (Singh et al., 2018; Sar et al., 2024; Naeem et al., 2024).

3.2 Weed Competition

Weed infestation is considered the most significant biological constraint in direct seeded rice (DSR), causing substantial yield losses ranging from 40% to 100% when left unmanaged. In dry direct seeded rice (DDSR), yield reductions due to uncontrolled weed growth can reach up to 96%, whereas in wet direct seeded rice (WDSR), losses of up to 61% have been reported (Shekhawat et al., 2020; Negi et al., 2024). Unlike puddled TPR, where 5–10 cm of standing water suppresses the germination of most weed species through oxygen exclusion and physical impediment, In DSR systems with limited or no standing water, weeds can germinate simultaneously with rice, resulting in intense competition of grasses (*Echinochloa* spp., *Leptochloa* spp.), sedges (*Cyperus* spp.), and broad-leaf species alongside rice seedlings. Weed communities in DSR are floristically more diverse and abundant than in TPR, and in the absence of effective management, pre-emptive competition between weed and rice seedlings determines the outcome of the crop season (Sen et al., 2020). Physiologically, rice varieties with high early seedling vigour characterized by rapid coleoptile and mesocotyl elongation, accelerated leaf area expansion, and prompt canopy closure confer a competitive advantage over weeds by pre-empting light interception and soil resource utilization during the 0–30 days after sowing (DAS) critical window (Namuco et al., 2009; Dimaano et al., 2020).

3.3 Root System and Nutrient Uptake

Although DSR promotes deeper root development relative to TPR, root growth under limited soil moisture and more soil aeration can be impaired by soil impedance (high bulk density, mechanical resistance), moisture stress, and micronutrient deficiencies. In sandy loam soils, DSR plants show higher nutrient requirements due to elevated plant densities and greater vegetative biomass production. Deeper root distribution particularly nodal roots extending beyond 30 cm is associated with improved nitrogen (N), phosphorus (P), and zinc (Zn) acquisition in aerobic soils (Panda et al., 2021; Ajmera et al., 2022; Deng et al., 2020).

3.4 Nutrient Imbalance and Reduced Nitrogen Use Efficiency

In aerobic DSR soils, nitrogen dynamics differ markedly from those in flooded TPR. The dominant N form under flooding is ammonium (NH_4^+), which is stable in anaerobic conditions and not subject to leaching. Under aerobic DSR conditions, NH_4^+ is rapidly nitrified to nitrate (NO_3^-) by soil bacteria (*Nitrosomonas* spp., *Nitrobacter* spp.), and the resulting NO_3^- is vulnerable to denitrification losses and leaching, particularly in coarse-textured soils. This results in lower NUE (30–40 kg grain/kg N in DSR versus 40–55 kg/kg N in TPR) and may necessitate split N application strategies (Negi et al., 2024; Sagare et al., 2020). Zinc and iron deficiencies are common in DSR fields, these deficiencies can significantly affect early crop establishment and overall plant vigour in direct seeded systems. Aerobic soils also tend to exhibit deficiencies in Zn (DTPA-Zn <0.6 mg/kg) and Fe (DTPA-Fe <4.5 mg/kg) due to the oxidized soil environment, which reduces the solubility and plant availability of both micronutrients (Kumar and Ladha, 2011).

3.5 Nematode Infestation

When employing DSR, specific soil-borne pathogens, particularly the root-knot nematode *Meloidogyne graminicola*, become problematic in the rice root zone. This nematode causes 16–32% yield losses in upland and rainfed rice in India, with approximately 2.6% grain reduction per 1,000 nematodes around young seedlings under upland conditions (Bridge et al., 2005; Khan and Ahamad, 2020). The aerobic soil environment of DSR is particularly conducive to nematode activity and reproduction, unlike the anaerobic flooded conditions of TPR, which limit nematode population growth.

4. Strategies to Overcome Constraints in Direct Seeded Rice

4.1 Genetic Improvement and Breeding for DSR Adaptation

Genetic enhancement is important for optimizing the performance and stability of rice in DSR systems, with breeding efforts targeting traits such as early seedling vigour, anaerobic germination tolerance, deep root system architecture, nitrogen and micronutrient use efficiency. Contemporary breeding methodologies amalgamate these physiological traits with molecular tools such as marker-assisted selection (MAS), QTL mapping, and genomic selection to accelerate variety development (Kumar et al., 2022a; Singh et al., 2022).

4.2 Early Seedling Vigour (ESV)

Early seedling vigour (ESV) is a key trait complex contributing to successful establishment and adaption of rice under DSR. In contrast to TPR seedlings protected by nursery conditions, DSR seedlings must sprout and develop under the full spectrum of aerobic field stresses from the moment of sowing (Anandan et al., 2020; Mahender et al., 2015).

From a physiological standpoint, ESV is closely associated with the efficient mobilization of stored seed reserves, particularly the degradation of starch facilitated by elevated α -amylase activity during germination. High α -amylase activity accelerates the conversion of starch to soluble sugars, fueling coleoptile elongation and early root initiation. Early vigour is also correlated with elevated early photosynthetic rates and accelerated chlorophyll accumulation, both of which facilitate the transition from heterotrophic (seed reserve-dependent) to autotrophic (photosynthesis-dependent) growth (Mahender et al., 2015; Yamane et al., 2018).

ESV is a complex quantitative trait governed by multiple genomic loci. Significant QTL clusters for ESV traits have been identified on chromosomes 3, 5 and 11 in rice, with the chromosome 11 cluster explaining up to ~30% of phenotypic variation for root length, seedling dry weight, and tiller number in direct seeded conditions (Sandhu et al., 2023; Singh et al., 2017). High-throughput digital imaging can precisely assess projected shoot area (cm²), leaf growth rate (mm²/day), and early biomass under DSR conditions, facilitating rapid screening of diverse germplasm panels (Anandan et al., 2020; Bian et al., 2022; Zhang and Zhang, 2018).

4.3 Anaerobic Germination (AG) Tolerance

DSR fields are vulnerable to transient waterlogging immediately after sowing due to heavy rainfall, inadequate drainage, or poor field levelling. Such anaerobic conditions suppress aerobic respiration in germinating seeds, although germinating rice can partially switch to anaerobic metabolism to sustain coleoptile elongation; genotypes lacking this capacity show markedly reduced germination and emergence (Kumar et al., 2022b; Chamara et al., 2018; Kunwar et al., 2024).

The physiological mechanism of AG tolerance centers on anaerobic carbohydrate metabolism. Under anoxia, mitochondrial respiration is suppressed; energy must instead be generated via anaerobic glycolysis and ethanol fermentation. AG-tolerant genotypes exhibit enhanced activation of α -amylase, starch phosphorylase, and key glycolytic enzymes, facilitating the catabolism of stored starch to soluble sugars that fuel coleoptile elongation. Critically, the trehalose-6-phosphate (T6P) signaling pathway regulates sugar sensing and energy availability under hypoxia. The AG1 locus, encoding a trehalose-6-phosphate phosphatase (OsTPP7), facilitates glucose transport in germinating seeds, enabling continued development under low-oxygen conditions (Mondal et al., 2020; Septiningsih et al., 2009). Marker-assisted backcrossing (MABC) of the AG1 locus into high-yielding, AG-sensitive cultivars has significantly enhanced germination rates and early establishment under flooded direct seeding (Miro and Ismail, 2013; Thapa et al., 2024).

From a breeding perspective, AG tolerance is assessed by measuring germination percentage, coleoptile length, root growth, seedling survival, and vigour indices under controlled waterlogged or nitrogen-flushed conditions. GWAS and QTL studies have identified loci on chromosomes 3, 7, and 9 associated with AG tolerance, providing molecular markers for MAS (Mendioro et al., 2014; Saimohan et al., 2021).

4.4 Root System Architecture (RSA)

Root system architecture (RSA) is of paramount importance in aerobic DSR environments, where soil moisture must be sourced from progressively deeper soil layers as the cropping season advances. The rice root system develops from the embryonic radicle (coleorhiza), followed by secondary adventitious (crown/nodal) roots arising from underground nodes. In upland (aerobic) conditions, the coleorhiza emerges first; under submergence, the coleoptile emerges before the coleorhiza, a distinction with implications for the establishment physiology of DSR (Chakraborty et al., 2017).

Key RSA parameters relevant to DSR adaptation include root length (cm), root angle (degrees from vertical), root branching density, specific root length (SRL, cm/g root DW), and root dry weight (g), as illustrated in Fig. 3. Genotypes with steeper root growth angles (<35° from vertical) develop deeper root systems, accessing subsoil moisture reserves during drought and enabling continued mineral nutrient uptake when surface soils dry out (Panda et al., 2021; Kitomi et al., 2020; Selamat and Nadarajah, 2021). The DEEPER ROOTING 1 (DRO1) gene, which regulates asymmetric auxin distribution and root gravitropism, is the primary genetic determinant of root growth angle in rice (Kitomi et al., 2020). DRO1 contributes to root-system architecture by promoting steeper root growth angles and deeper rooting, whereas qDTY1.1, qDTY3.1 and qDTY12.1 are associated primarily with grain yield under drought stress. These loci represent complementary genetic resources for improving different components of rice adaptation to water-limited environments. (Kitomi et al., 2020; Selamat and Nadarajah, 2021). Phenotyping RSA has been advanced by rhizotron systems, root scanners (WinRHIZO), X-ray computed tomography (CT), and shovelomics a rapid, field-applicable method for quantifying root angle and branching density at the tillering stage (Anand et al., 2025).

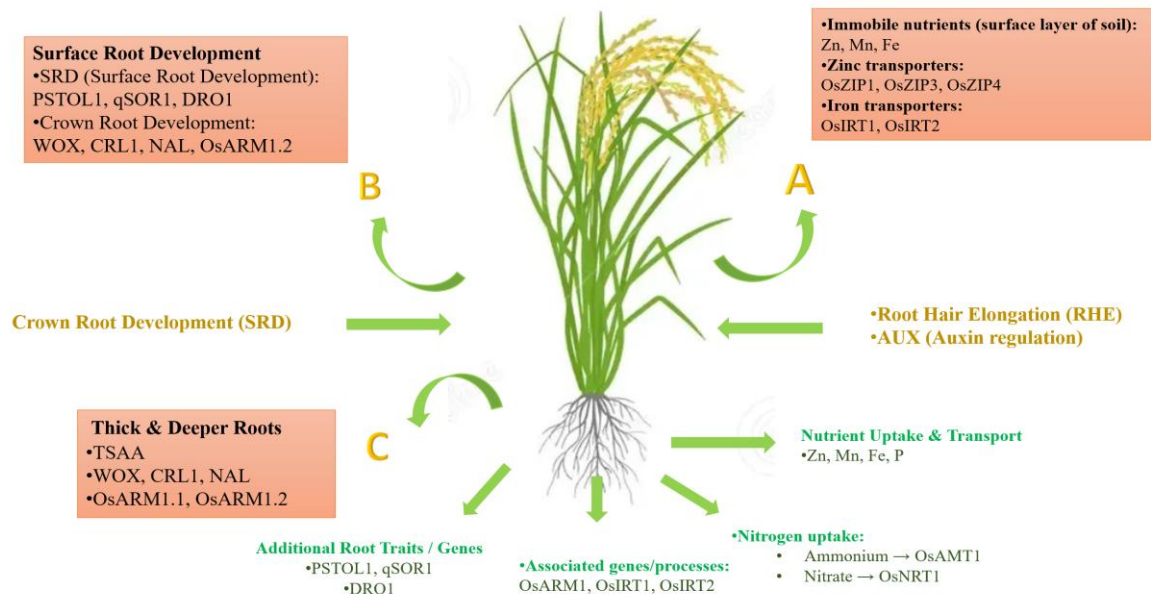


Fig 3. Schematic representation of root traits, nutrient transporters, and hormonal regulation in direct seeded rice

This schematic diagram illustrates the genetic networks, hormonal regulations, and physiological adaptations governing rice root architecture and nutrient acquisition. On the left, genetic regulators like *PSTOL1*, *DRO1*, and *WOX* orchestrate specialized structural modifications, including surface, crown, and deep root development. Concurrently, the right and subterranean pathways detail how auxin-regulated root hair elongation and specific transporter families (*OsZIP*, *OsIRT*, *OsAMT1*, *OsNRT1*) actively optimize macro- and micronutrient uptake.

4.5 Seed hardening techniques

Seed priming is among the most effective pre-sowing interventions for improving germination and early establishment in DSR. Hydropriming (water soaking for 12–24 h) and Osmo priming (treatment with polyethylene glycol at –0.8 MPa for 24 h) both activate metabolic processes including starch mobilization, membrane repair, and antioxidant enzyme (superoxide dismutase, catalase) induction prior to radicle emergence, resulting in accelerated and more synchronized germination. Primed seeds exhibit higher germination percentages, reduced mean germination time (MGT), improved SVI, and greater seedling dry weight compared with unprimed seeds under DSR conditions (Miah et al., 2022). Seed coating with micronutrients (ZnSO_4 at 0.5–2% w/w) provides Zn nutrition during the critical seedling establishment phase, while incorporation of plant growth-promoting rhizobacteria (PGPR such as *Bacillus* spp. and *Pseudomonas fluorescens*) into seed coatings enhances root development, Fe solubilization, and P availability. Important physiological traits associated with adaptation to DSR systems, together with their phenotyping methods, measurement units, and reported ranges of variation across diverse rice germplasm, are presented below (Miah et al., 2022; Vlamincx et al., 2020) (Table 2)

4.6 Integrated Weed Management (IWM)

Given that weed infestation is the primary biological constraint in DSR, an integrated weed management (IWM) approach encompassing chemical, genetic, mechanical, and cultural interventions is essential. Pre-emergence herbicides such as pendimethalin (1.0 kg a.i./ha) applied within 24–72 h of sowing inhibit the germination of grass and broadleaf weed species through disruption of cell division (Singh et al., 2018; Sar et al., 2024; Sanodiya and Singh, 2017). Post-emergence herbicides such as bispyribac-sodium (25 g a.i./ha at 15–20 DAS) effectively control *Echinochloa* spp., *Cyperus* spp., and broadleaf weeds that escape pre-emergence control. The stale seedbed technique, pre-sowing irrigation to stimulate weed germination, followed by a non-selective herbicide flush before rice sowing, reduces the initial weed seed bank by 40–60% (Singh et al., 2018; Sar et al., 2024; Sanodiya and Singh, 2017). Competitive rice cultivars with high ESV, early canopy closure ($\text{LAI} > 3$ by tillering), and greater seedling biomass are a key biological complement to chemical control, reducing reliance on herbicides and suppressing weed growth through canopy shading and resource pre-emption (Namuco et al., 2009; Dimaano et al., 2020).

4.7 Water Management Strategies

Alternate wetting and drying (AWD) is the most widely validated irrigation strategy for DSR. AWD involves allowing the soil to dry to a threshold (typically –15 to –20 kPa measured by a field water tube or tensiometer at 15–20 cm depth) before re-irrigation (Chu et al., 2018; Gilardi et al., 2023). AWD typically saves 150–250 mm of irrigation water per season (20–30% reduction), reduces CH_4 emissions by 40–70%, and maintains grain yield within $\pm 5\%$ of continuously flooded irrigation when applied correctly. Precision soil moisture monitoring using tensiometers, capacitance sensors, and digital data-loggers enables site-specific irrigation scheduling, preventing

both drought stress at critical periods (tillering, flowering) and waterlogging that would promote nematode populations (Bagada et al., 2025).

4.8 Micronutrient Deficiency Management

In aerobic DSR soils, the oxidized soil environment accelerates the conversion of Fe^{2+} to Fe^{3+} (reducing Fe bioavailability) and reduces Zn mobility, particularly in alkaline and well-buffered soils. Effective Zn management includes soil application of ZnSO_4 at 25 kg/ha, seed treatment (0.5–2.0% ZnSO_4), and foliar sprays at the tillering stage. Genetic approaches utilizing Zn-efficient genotypes with enhanced expression of OsZIP family transporter genes (OsZIP4, OsZIP5, OsZIP8) can improve Zn absorption and root-to-shoot translocation (Kumar and Ladha, 2011). Fe deficiency (interveinal chlorosis on young leaves) is corrected by Fe-EDTA soil application, foliar sprays (0.5–1.0% at tillering), or PGPR with siderophore-producing capacity, while OsIRT1 and OsIRT2 gene-based tolerance provides longer-term genetic solutions (Selamat and Nadarajah, 2021). Micronutrient and macronutrient deficiency management in DSR, including deficiency symptoms, diagnostic thresholds, corrective management strategies and their effects on crop growth and yield response are presented in Table 2

Table 2. Remedy for nutrient deficiency symptoms in DSR

Nutrient	Deficiency Symptom in DSR	Soil / Plant Threshold	Management Strategy	Reported Yield Response	Reference
Zinc (Zn)	Interveinal chlorosis on young leaves; 'khaira' disease; stunted growth; reduced tillering	Soil DTPA-Zn <0.6 mg/kg has been reported as a deficiency indicator; critical values vary with soil and plant growth stage	Soil application: ZnSO_4 at 25 kg/ha (or) Foliar spray of 0.5% ZnSO_4	0.5% ZnSO_4 nutripriming increased grain yield from 4088 to 4629 kg/ha	(Bautista et al., 2023; Tripathy et al., 2021; Jawahar et al., 2019)
Iron (Fe)	Interveinal chlorosis on young leaves (bronzing); necrosis in severe cases; reduced photosynthesis	Soil DTPA-Fe <4.5 mg/kg under dry-DSR conditions	Foliar spray of 0.5% FeSO_4	0.5% FeSO_4 Nutri priming increased grain yield from 4088 to 4652 kg/ha	(Jawahar et al., 2019; Abhishek et al., 2023; Vijayakumar et al., 2019)
Nitrogen (N)	Yellowing of older leaves; reduced LAI; stunted growth; poor tiller number	SPAD <32 indicate low N status, values vary with growth stages	Split N application: basal DAP + top-dress urea at tillering and panicle initiation; site-specific N management (SSNM); nitrification inhibitors (DCD, DMPP) to reduce leaching (Subedi et al., 2018; Sen et al., 2020)	N management increase canopy development, yield and N-use efficiency. Rice Crop Manager-based SSNM increased DSR grain yield by 19% compared with farmer fertilizer practice .	(Jawahar et al., 2019)
Potassium (K)	Scorched leaf margins; weak stems (lodging); poor grain filling; reduced disease resistance	P availability depends strongly on soil properties	Basal or split application if leaching-prone sandy soils; K fertigation in DSR-AWD systems	K management improves grain filling, plant stress and yield under K-deficient conditions. 60 kg/ha, applied half basally and a half at panicle initiation, produced 5.4 t/ha grain yield, about 10% higher than full basal application	(Jawahar et al., 2019)

DTPA = diethylenetriaminepentaacetic acid; DW = dry weight; LAI = leaf area index; SPAD = soil plant analysis development units; SSP = single superphosphate; DAP = diammonium phosphate; MOP = muriate of potash; IAA = indole-3-acetic acid; SOD = superoxide dismutase; CAT = catalase.

5. Physiological Screening for DSR Adaptation

5.1 Early Seedling Vigour

Traditional assessments of ESV include germination percentage (GP, %), germination energy (GE, %), germination index (GI), mean germination time (MGT, days), seedling vigour index (SVI = Germination % × Seedling length(cm)), shoot length (cm), root length (cm), and seedling dry weight (mg) determined after 7–14 days (Anusha et al., 2018; Krishna et al., 2025a). Significant genotypic variation for these parameters exists within the *O. sativa* gene pool; for example, in one germplasm evaluation SVI ranged from <100 in weak-vigour types to >2,500 in high-vigour DSR-adapted genotypes.

Advanced HTP platforms using RGB and near-infrared (NIR) cameras coupled with automated image analysis software (e.g., ImageJ, PlantCV, SmartGrain) enable non-destructive, continuous monitoring of projected shoot area (cm²), leaf area (cm²), biomass accumulation (g, estimated from NDVI), and canopy development rate across large populations (Anandan et al., 2020; Zhang and Zhang, 2018). These image-derived metrics show strong positive correlations ($r = 0.80\text{--}0.95$) with conventional destructive measurements, validating HTP for germplasm screening (Anandan et al., 2020; Krishna et al., 2025) (Table 3)

Table 3. Physiological traits for DSR system

Physiological Trait	Parameter	Phenotyping Method	Scale	Reference
Early seedling vigour (ESV)	Seedling vigour index	Germination test + seedling length; digital imaging (projected shoot area, cm ²)	SVI: 100–2500; high-vigour genotypes germinate 30–50% faster than low-vigour	(Anandan et al., 2020; Mahender et al., 2015; Dey et al., 2026)
Germination percentage (GP)	% seeds germinated at 7 days	Standard ISTA roll-towel test at 25°C; field emergence count (plants/m ²)	GP: 41-100% varies with genotype and treatment	(Anusha et al., 2018; Krishna et al., 2025a; Quilloy et al., 2021)
Coleoptile elongation	Coleoptile length (mm) at 5 days	Measured under anaerobic (flooded, 5 cm water) conditions; digital ruler	60-90mm in tolerant genotypes; <20mm in sensitive genotypes	(Chamara et al., 2018; Miro and Ismail, 2013; Illangakoon et al., 2019; Mwakyusa et al., 2023)
Mesocotyl length	Mesocotyl length (mm) at 7 days under deep sowing (5 cm)	Deep-sowing experiments; root scanner imaging	Long mesocotyl (>40 mm) associated with improved emergence from deep sowing	(Kanno et al., 2023)
Root length (RL)	Total root length (cm) per plant	Root scanner (WinRHIZO); rhizotron imaging; minirhizotron tubes	RL: 33.43-98.40cm under well watered condition; 42.38-127.06cm under water stress	(Maila et al., 2025)
Root angle	Root growth angle (°) from vertical	Soil-filled tubes; X-ray CT; paper-roll assay; shovelomics at tillering	45.60-56.63 ° under well-watered condition; 41.26-61.98° under water stress	(Kitomi et al., 2020; Selamat and Nadarajah, 2021; Maila et al., 2025)
Specific root length (SRL)	cm root/g root dry weight	WinRHIZO analysis after root wash; gravimetric dry weight	High SRL indicates fine roots; improved P and water foraging in aerobic soils	(Selamat and Nadarajah, 2021; Maila et al., 2025)
Leaf area index (LAI)	m ² leaf area/m ² ground	Ceptometer (AccuPAR LP-80); hemispherical photography; UAV multispectral imaging	4.39-4.70 in the reported DSR experiment	(Negi et al., 2024; Dimaano et al., 2020; Midya et al., 2021)
Chlorophyll content (SPAD)	SPAD units	Portable SPAD-502 chlorophyll meter on flag leaf; reflectance indices (NDRE)	SPAD 35–55 as a reported physiological range, varies with genotype and growth stage	(Negi et al., 2024; Vlamincx et al., 2020)
Photosynthetic efficiency (Pn)	Photosynthetic rate	Li-COR LI-6400/LI-6800 portable gas analyzer; measured at 1000 µmol photons/m ² /s	Pn: 23.55 µmol CO ₂ /m ² /s in anaerobic germination experiment	(Vinitha et al., 2024)
Stomatal aperture	Stomatal conductance (gs)	Li-COR LI-6400; porometer; thermal imaging (canopy temperature proxy)	Reflects stomatal regulation and varies with atmospheric conditions, water status and genotype.	(Chaudhary et al., 2023)

Water loss from leaves	Transpiration efficiency (TE)	Gravimetric pot studies; ^{13}C isotope discrimination ($\Delta^{13}\text{C}$, ‰)	Depends on the environment conditions, the method of estimation and the genotype.	(Anand et al., 2025; Ajaykumar et al., 2025)
Chlorophyll fluorescence	Fv/Fm ratio	Portable chlorophyll fluorometer (Handy PEA, FluorPen FP 110)	Remains high under controlled conditions and decreases when stress is imposed	(Negi et al., 2024; Vlamincx et al., 2020)
Greenness	NDVI (canopy vigour)	UAV multispectral (RedEdge-MX); ground-based handheld sensors (GreenSeeker)	Provides a relative measure of canopy biomass and greenness and varies with canopy condition and growth stage	(Vlamincx et al., 2020)
Canopy temperature	°C below air temperature	Infrared thermometer (IR gun); thermal UAV camera; thermocouple psychrometer	Reflects canopy cooling capacity and varies with atmospheric demand. genotype and water availability	(Anand et al., 2025; Chaudhary et al., 2023)

SPAD = Soil Plant Analysis Development; NDVI = Normalized Difference Vegetation Index; LAI = leaf area index; DAS = days after sowing; CTD = canopy temperature depression; PRI = photochemical reflectance index; IR = Infrared thermometer; FluorPen= Fluorescence Pen; NDRE = Normalized Difference Red Edge Index.

5.2 Anaerobic Germination Tolerance

Germplasm evaluation for AG tolerance involves standardized screening protocols where seeds are submerged in 5 cm of stagnant water for 7–10 days in the dark at 30°C, followed by recovery under normal conditions for an additional 7 days (Vinitha et al., 2024; Illangakoon et al., 2019). Traits measured include coleoptile length (mm), germination percentage under anaerobic stress (AG-GP, %), post-stress seedling survival (%), and SVI under anaerobic conditions. Genotypic differences are substantial: tolerant genotypes such as Khao Hlan On, Ma-Zhan Red, and AG1/AG2 QTL introgression lines exhibit coleoptile lengths of 60–90 mm and AG-GP >70%, compared with <20 mm and <30% in sensitive varieties such as IR64 (Chamara et al., 2018; Miro and Ismail, 2013; Illangakoon et al., 2019; Mwakyusa et al., 2023).

5.3 Root System Architecture

RSA evaluation in germplasm involves both controlled-environment and field-based approaches. Under controlled conditions, root morphology is quantified using paper-roll germination assays (measuring primary root length, lateral root number, root angle), gel-based root phenotyping (transparent agar or gel chambers), and hydroponics. In the field, shovelomics provides rapid, non-destructive assessment of nodal root angle, root branching density, and root number at the tillering stage (Panda et al., 2021; Selamat and Nadarajah, 2021; Maila et al., 2025). Advanced root imaging technologies, including rhizotrons (glass-fronted observation chambers), flatbed root scanners (Epson Expression 11000XL with WinRHIZO Pro software), and X-ray CT enable non-destructive 3D reconstruction of root systems with quantification of root depth, angle, diameter distribution, and surface area (Selamat and Nadarajah, 2021).

Key RSA traits for DSR adaptation, summarized in Fig. 4, include: root length density (RLD, cm root/cm³ soil) in the 20–60 cm soil layer; specific root length (SRL, cm/g DW, indicating root fineness and P/water foraging capacity); root angle (<35° for deep-rooting genotypes); and nodal root number (higher numbers improve nutrient capture) (Panda et al., 2021; Maila et al., 2025; Liu et al., 2022)

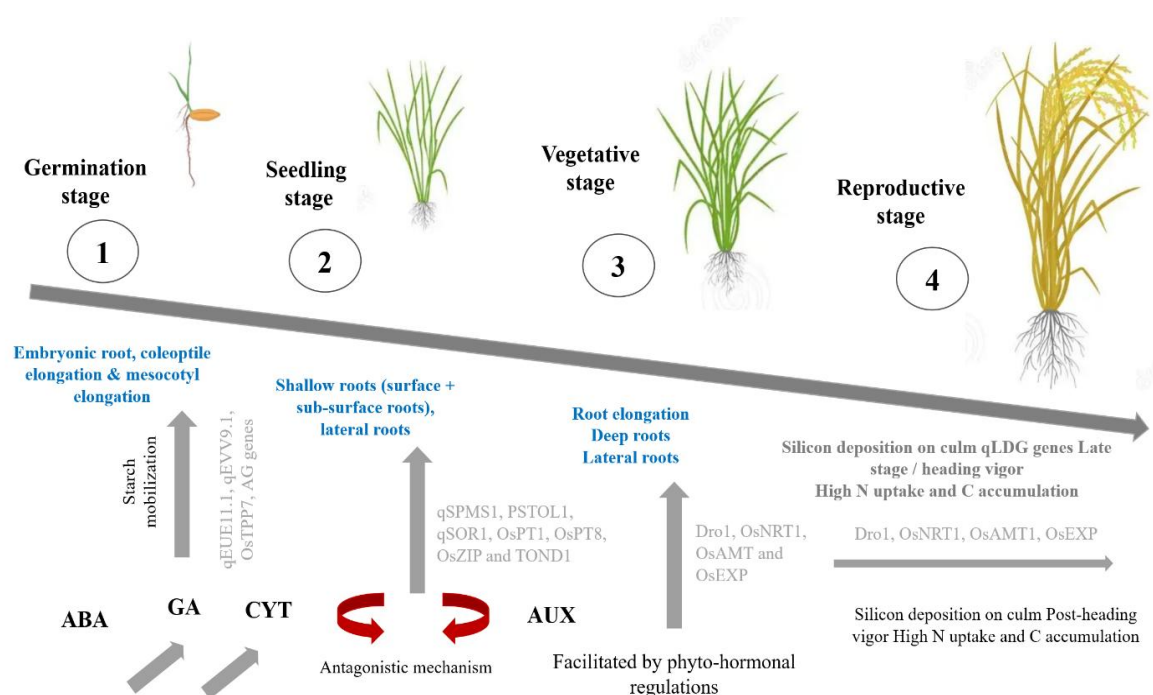


Fig 4. Morphological and molecular regulation of root growth across rice developmental Stages

This schematic illustrates the growth stages of rice and the physiological and hormonal regulations influencing development. During germination, embryonic root, coleoptile, and mesocotyl elongation are driven by starch mobilization and interactions between ABA, gibberellins, and cytokinin. In the seedling and vegetative stages, auxin-mediated regulation enhances shallow, deep, and lateral root development to improve nutrient and water acquisition. Finally, during the reproductive stage, genes associated with nutrient uptake and silicon deposition boost culm strength, vigour, and efficient carbon and nitrogen accumulation to maximize overall crop performance.

5.4 Photosynthetic Efficiency and Biomass Traits

Photosynthetic efficiency is quantified through multiple complementary methods. Portable SPAD-502 meters provide non-destructive, instantaneous estimates of leaf chlorophyll content (proportional to SPAD units, 0–100), which correlates strongly with leaf N concentration and photosynthetic capacity ($r^2 = 0.70\text{--}0.85$). Li-COR LI-6400 or LI-6800 portable photosynthesis systems are the gold standard for measuring net photosynthetic rate (P_n , $\mu\text{mol CO}_2/\text{m}^2/\text{s}$), stomatal conductance (g_s , $\text{mol H}_2\text{O}/\text{m}^2/\text{s}$), intercellular CO_2 concentration (C_i , $\mu\text{mol CO}_2/\text{mol}$), and transpiration rate (E , $\text{mmol H}_2\text{O}/\text{m}^2/\text{s}$) at the leaf level (Chaudhary et al., 2023; Ajaykumar et al., 2025).

Chlorophyll fluorescence analysis provides insight into the operational efficiency of photosystem II (PSII). The F_v/F_m ratio (maximum PSII efficiency, measured after dark adaptation) is a sensitive indicator of photoinhibition and stress: healthy leaves exhibit F_v/F_m of 0.78–0.84, while drought-, chilling-, or nutrient-stressed leaves show values <0.70 . The effective PSII quantum yield (ΦPSII), electron transport rate (ETR), and non-photochemical quenching (NPQ) provide additional information on dynamic photoprotective responses (Negi et al., 2024).

At the canopy scale, UAV-mounted multispectral cameras (e.g., DJI Phantom 4 Multispectral, Parrot Sequoia+) capture vegetation indices including NDVI (Normalized Difference Vegetation Index), NDRE (Normalized Difference Red Edge), and PRI (Photochemical Reflectance Index). NDVI correlates strongly with green biomass and chlorophyll content, enabling rapid, non-destructive screening of canopy vigour, stress responses, and yield potential across entire field trials (Itoh et al., 2005; Ma et al., 2022). Thermal infrared (TIR) cameras measure canopy temperature ($^{\circ}\text{C}$), with canopy temperature depression (CTD, $^{\circ}\text{C}$ below air temperature) serving as a proxy for stomatal conductance and drought tolerance (Chaudhary et al., 2023).

5.5 Combined Trait Indexing and Multi-Environment Screening

Effective DSR phenotyping increasingly relies on the integration of multiple physiological data streams into composite indices. The stress tolerance index, $\text{STI} = (Y_p \times Y_s) / (\bar{Y}_p)^2$; Y_p =yield under stress; Y_s =yield under control and composite vigour indices incorporate germination rate, early biomass, root architecture, and photosynthetic efficiency scores into a single, tractable selection criterion (Singh et al., 2017). Multi-trait indices circumvent the limitations of single-trait selection, since individual traits may not adequately reflect overall performance under the complex, multi-stress environment of DSR.

Multi-environment testing is essential for capturing genotype $\times$ environment ($G \times E$) interactions, which are substantial in DSR due to wide variation in soil texture, moisture regime, temperature, and weed pressure across locations and seasons. AMMI (Additive Main effects and Multiplicative Interaction) models and GGE (Genotype + Genotype-by-Environment) biplot analysis are standard statistical tools for identifying broadly adapted and specifically adapted genotypes (Yamane et al., 2018). Machine learning approaches including random forests, gradient boosting, and artificial neural networks are increasingly applied to large multi-trait, multi-environment datasets to improve selection accuracy and accelerate breeding cycles (Gong et al., 2024). Major quantitative trait loci (QTLs) and genes associated with important physiological traits contributing to adaptation in direct seeded rice systems are presented below (Table 4)

Table 4. Major quantitative trait loci (QTLs) and genes associated with physiological traits for DSR systems.

Physiological trait	QTL / Gene	Chr.	Associated trait, physiological function and breeding significance	Reference
Early vigour	qAEV1.5	1	Early vigour score and mesocotyl length under aerobic conditions; potential target for improving early crop establishment	(Gong et al., 2024)
	qAEV8	8	Early vigour score under aerobic DSR conditions; large-effect QTL in japonica rice, associated with early biomass variation and potential for marker-assisted improvement	(Gong et al., 2024)
Early vigour	QTLs Chr 3 & 5 (Swarna $\times$ Moroberekan)	3, 5	Associated with Shoot length, stem length, total dry weight; potential hotspot for improving early establishment and weed competitiveness	(Singh et al., 2017)
Anaerobic germination (AG)	AG1 locus (OsTPP7)	9	Trehalose-6-phosphate phosphatase; maintains glucose supply; improves coleoptile elongation under submergence, potential target for improving DSR establishment under transient flooding	(Mondal et al., 2020; Septiningsih et al., 2009; Miro and Ismail, 2013; Thapa et al., 2024)
Anaerobic germination	qAG3	3	Associated with seedling survival under anaerobic conditions; improves stand density in rainfed DSR	(Baltazar et al., 2019)

Anaerobic germination	qAG7.1, qAG7.2, qAG7.3 (IR64 × Kharsu 80A)	7	Multiple QTLs associated with seedling survival under anaerobic conditions; potential donor loci for improving DSR establishment	(Baltazar et al., 2019; Nishimura et al., 2020)
Drought tolerance	qDTY1.1	1	Associated with Grain yield under reproductive-stage drought; maintains panicle number and spikelet fertility; potential target for improving yield stability under water limited conditions	(Selamat and Nadarajah, 2021)
	qDTY3.1	3	Associated with Grain yield under mild to moderate drought; linked to deeper root and stay-green; potential target for drought adaptation breeding	(Selamat and Nadarajah, 2021)
Drought tolerance	qDTY12.1	12	Associated with Grain yield under severe drought; sustains photosynthesis and transpiration efficiency; potential target for improving yield stability under water limited conditions	(Selamat and Nadarajah, 2021)
Root angle and deep rooting	DRO1 gene	9	Auxin-mediated root gravitropism; steeper root angle; increased subsoil moisture access; yield improvement under drought	(Kitomi et al., 2020)
Seed germination & early growth	Multiple additive loci (GWAS – Yang et al.)	Multiple	Germination index, shoot length, root length	(Sagare et al., 2020)
Nitrogen use efficiency	OsNRT1.1B (nitrate transporter)	10	Effective Nitrate uptake; potential target for improving nitrogen acquisition	(Sagare et al., 2020)

Zinc efficiency	OsZIP4, OsZIP5, OsZIP8 (ZIP family)	Multiple	Zinc uptake and root-to-shoot translocation; key in aerobic soils prone to Zn deficiency	(Kumar and Ladha, 2011)
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Chr. = chromosome; GWAS= Genome Wide Association Study; AG = anaerobic germination.

6. High Throughput Phenotyping and Genomics Integration

The deployment of HTP platforms has transformed the capacity to screen large rice germplasm collections for DSR-adaptive traits. UAV-based imaging equipped with RGB, multispectral, and thermal sensors can survey hundreds of field plots in a single flight, capturing canopy height, NDVI, canopy temperature, and fractional ground cover with sub-centimeter spatial resolution (Selamat and Nadarajah, 2021; Vlaminc et al., 2020). This enables breeders to identify vigorous, early-canopy-closing genotypes rapidly and at scale - a critical capability when evaluating diversity panels of 300 –3,000 accessions.

Root phenotyping platforms including rhizotrons, gel-chamber assays, and X-ray CT provide non-destructive evaluation of root depth, angle, diameter distribution, and branching architecture. These technologies facilitate the identification of genotypes with deep, steep root systems suited to aerobic DSR conditions (Selamat and Nadarajah, 2021). The integration of HTP data with genomic information through genomic selection (GS) models enables the prediction of breeding values for complex, polygenic traits such as yield under drought and early vigour from marker data alone, accelerating genetic gain per year. Seed enhancement technologies, water management strategies, and weed control methods employed for improving crop establishment, early seedling growth, resource-use efficiency and productivity in direct seeded rice (DSR) systems are presented below (Table 5).

Table 5. Seed enhancement technologies, water management strategies, and weed control methods for improving crop establishment and productivity in DSR

Technology / Strategy	Mechanism / Description	Measured Response (unit)	Reported Benefit in DSR	Reference
Hydropriming	Pre-sowing hydration to promote uniform germination and early seedling development	Germination rate emergence rate index (ERI); seedling dry weight (mg)	Response varied with priming duration sowing conditions and genotype	(Miah et al., 2022)
Osmopriming	Controlled hydration using osmotic solutions to stimulate pre-germinative metabolic activity	Mean germination time; seedling vigour index (SVI)	Treatment-dependent effects were reported for PEG	(Miah et al., 2022)
Zinc seed coating (ZnSO ₄ , 0.5–2.0% w/w)	Zinc applied as seed coating; Zn available during early seedling growth; activates metalloenzymes (Cu-Zn SOD)	Seedling Zn concentration (mg/kg DW); root length (cm); shoot dry weight (mg/seedling)	ZnSO ₄ concentrations of 0.5-2% were used for seed treatment	(Kumar and Ladha, 2011; Yang et al., 2019)
PGPR inoculation (<i>Bacillus</i> spp., <i>Pseudomonas fluorescens</i>)	Plant growth-promoting rhizobacteria produce IAA, siderophores, ACC deaminase; improve root architecture and Fe/P solubilisation	Root dry weight (g); nodal root number; Fe uptake (mg/plant); P uptake (mg/plant)	Responses varied according to bacterial strain, nutrient availability	(Miah et al., 2022; Vlaminc et al., 2020)
Alternate wetting and drying (AWD)	Limits continuous soil saturation while maintaining adequate crop water supply	Irrigation water savings (mm/season); CH ₄ emission (kg CH ₄ /ha/season); grain yield (t/ha)	15-30% reduction in total water input and 20-50% reduction in irrigation water use	(Chu et al., 2018; Gilardi et al., 2023)
Laser land levelling	Encourages emergence of weeds before crop establishment	Coefficient of variation (CV%) of seedling	Weed population reduction of upto 40% and weeding-labour savings of 75% have been reported	(Singh et al., 2018; Sar et al., 2024; Sanodiya

		emergence; weed dry weight (g/m ²)		and Singh, 2017)
Stale seedbed technique (pre-sowing flush irrigation)	Pre-sowing irrigation to stimulate weed germination; weeds killed with non-selective herbicide before sowing	Weed seed bank reduction (%); weed density at 30 DAS (plants/m ²)	Weedy-rice density declined by 39.83-63.72%	(Singh et al., 2018; Sar et al., 2024; Sanodiya and Singh, 2017)
Pre-emergence herbicide (Pendimethalin, 1.0 kg a.i./ha)	Applied within 24–72 h of sowing; disrupts cell division in germinating weed seeds; soil-incorporated by light irrigation	Weed control efficacy (%); crop phytotoxicity score (1–9 IRRI scale)	75% reduction in weed biomass has been reported	(Singh et al., 2018; Sar et al., 2024; Sanodiya and Singh, 2017)
Post-emergence herbicide (Bispyribac-sodium, 25 g a.i./ha)	ALS inhibitor; applied at 15–20 DAS; effective against <i>Echinochloa</i> spp., <i>Cyperus</i> spp., and broadleaf weeds	Weed biomass and yield loss	>75% reduction in weed biomass has been reported	(Singh et al., 2018; Sar et al., 2024; Sanodiya and Singh, 2017)

DAS = days after sowing; a.i. = active ingredient; AWD = alternate wetting and drying; FFI = fully flooded irrigation; GP = germination percentage; SVI = seedling vigour index; ERI = emergence rate index; MGT = mean germination time; PGPR = plant growth-promoting rhizobacteria.

GWAS in diverse germplasm panels has extended the genetic architecture of DSR adaptation beyond what is detectable in bi-parental populations. A GWAS of a japonica diversity set under aerobic conditions identified two large-effect QTLs qAEV1.5 (Chr. 1, PVE ~13.5%) and qAEV8 (Chr. 8, PVE ~22.1%) for early vigour score and mesocotyl length, providing markers for MAS in japonica breeding programs (Gong et al., 2024). Integrating GWAS results with gene expression data (RNA-seq) and functional genomics (CRISPR/Cas9 validation) is increasingly used to identify and validate candidate genes such as OsCPS1 for seedling length and OsTPP7 for AG tolerance for precision breeding (Dimaano et al., 2020; Thapa et al., 2024; Ma et al., 2022).

Note:

GWAS: Genome-Wide Association Study. It uses thousands to millions of SNP markers distributed throughout the genome to identify marker–trait associations.

QTL mapping / Quantitative trait locus (QTL) mapping is used to link a physical or measurable phenotypic trait to specific genomic regions or molecular marker

Genomic selection: An advanced breeding method that uses genome-wide DNA markers and statistical prediction models to estimate the breeding value of plants and animals before full field testing

Marker-Assisted Selection (MAS) is a molecular breeding approach that uses DNA markers tightly linked to causal genes or QTL to infer genotype

Gene editing is a technique that allows scientists to change DNA by adding, removing, or altering genetic material at specific locations, commonly using tools like CRISPR-Cas9

7. Future Aspects

Direct seeded rice future research focus on improving crop establishment, resource use efficiency, stress adaptation and yield stability across diverse production environments.(Ma et al., 2022; Li et al., 2023; Devkota et al., 2020) Genomics-assisted breeding, combined with high-throughput phenotyping, GWAS, genomic selection and gene editing approaches can be used to identify and evaluate allele associated with early seedling vigour, anaerobic germination tolerance, drought response, root system architecture and NUE(Dey et al., 2026).However, the performance of individual loci should be validated across genetic backgrounds and target environments before their wider use in breeding.

Digital phenotyping and precision agriculture can improve the measurement and management of soil moisture, crop stress, nutrient status and weed pressure. UAV and satellite-based sensing together with the field-based physiological measurements may support spatial assessment of resource use and crop performance (Jat et al., 2022; Alam et al., 2020; Dhanda et al., 2022). Future research should also focus on developing cultivars with enhanced competitive ability against weeds, combining the physiological traits of high ESV and rapid canopy closure with tolerance of reduced herbicide use. Physiological screening, molecular breeding, and precision agronomy must be systematically integrated to realize the full potential of DSR as a climate-resilient, resource-efficient rice production system.

8. Bibliometric overview of the literature reviewed:

A bibliometric analysis was conducted to identify publication trends and major research themes related to direct seeded rice (DSR). Publications were retrieved from the **Scopus** database using the search string: “rice”, “direct seeded rice”, “QTL”, “phenotyping” and “early seedling vigour”. The search was conducted on **13/7/2026**. The initial search yielded 1527 records. After removal of duplicate, irrelevant and incomplete records according to the predefined inclusion and exclusion criteria, **90 publications** were retained for analysis.

Publications were included when they were directly related to direct seeded rice and addressed aspects such as crop establishment, physiological adaptation, agronomic management, phenotyping, nutrient use, water management or genetic improvement. Records that were unrelated to rice, unrelated to direct seeding, duplicate records, or lacked sufficient bibliographic information were excluded.

The bibliographic information, including publication year, source journal, author information and author keywords, was exported from Scopus in **CSV format**. The data were analysed using **Python**. The python version: 3.12.3 is used to generate the bibliometric analysis. the module named pandas, is used for Reading the Scopus Excel file, tabulating/grouping all output tables, writing the multi-sheet Excel workbook, All chart rendering is done through module matplotlib and the numeric operations are handled by numpy module of Python. Publication trends, source journals, co-authorship patterns, author keywords and temporal keyword distributions were examined. The analyses were used to describe the research landscape and identify major themes represented in the dataset.

For reproducibility, the database, search string, search date, screening criteria, number of retrieved and retained records, data-processing procedure and software used are reported. The bibliometric results were interpreted descriptively, particularly for recent years where the number of publications was limited was summarized as Fig 5-9.

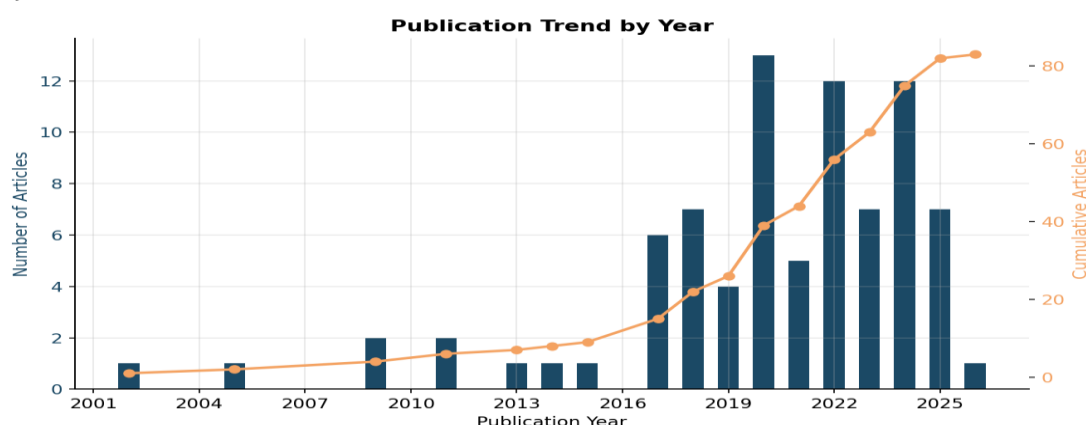


Fig. 5. Year-wise publication trend and cumulative growth in DSR (2001-2026)

The bar chart represents the trend in publications from the year 2001 to 2026. The growth increased sharply from 2017, peaking at 13 publications in 2020 and remaining high throughout 2025. This increase in the publication trend reflects research focus on traits like early seedling vigour, anaerobic germination and root architecture driven by labor shortages, water scarcity and climate concerns.

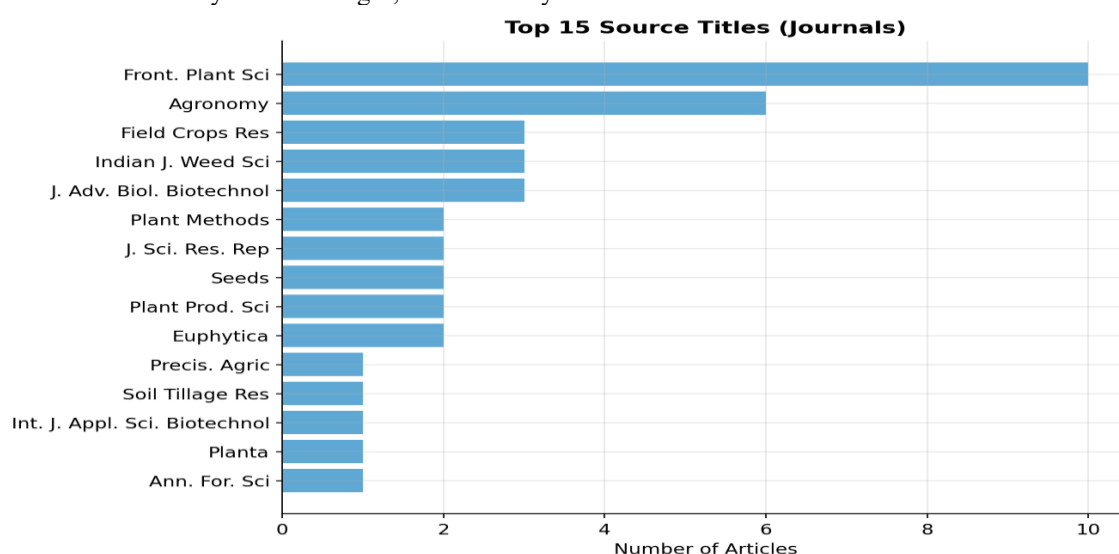


Fig. 6. Top 15 source journals by number of publications in DSR

The graph represents the journals focusing on the physiological phenotyping in DSR. Frontiers in plant science leads with 10 articles, followed by Agronomy with 6 articles, Field Crops Research, the Indian Journal of Weed Science, and the Journal of Advanced Biology and Biotechnology each contributed 3 articles. This distribution reflects the multidisciplinary nature of DSR research, linking different aspects of science such as the agronomy, weed science and physiology.

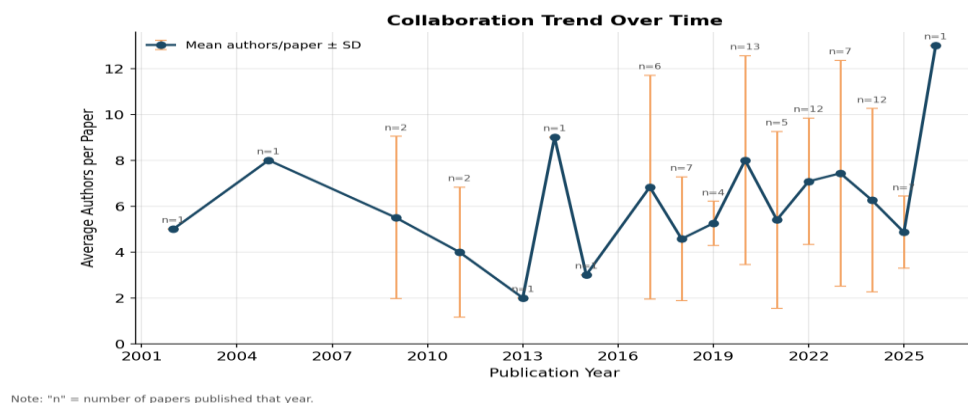


Fig. 7. Trend in average number of co-authors per publication over time.

The graph shows the mean number of authors per publication for each year, with error bars ($\pm$ SD, where n greater than 1) and the number of publications(n) underlying each year's estimate labelled above the point. Values fluctuate considerably across the 17 years with the available data: an early rise from 5(2002) to 8 (2005) is followed by a decline to 2 in 2013 and a sharp spike to 9 in 2014, before easing to 3 in 2015. From 2017 onward, year-on-year means range between roughly 4.5 and 8 authors per paper, generally supported by large sample(n=4-13). The apparent peak of 13 authors per paper in 2026 is based on a single publication(n=1), as are five other years in the series (2002,2005,2013,2014 and 2015); these single-publication years, visible from their minimal error bars, should not be read as evidence of a sustained collaboration trend. seventeen years in this dataset are represented by a single publication each and the 2025-2026 figure is one such case rather than evidence of collaboration trend.

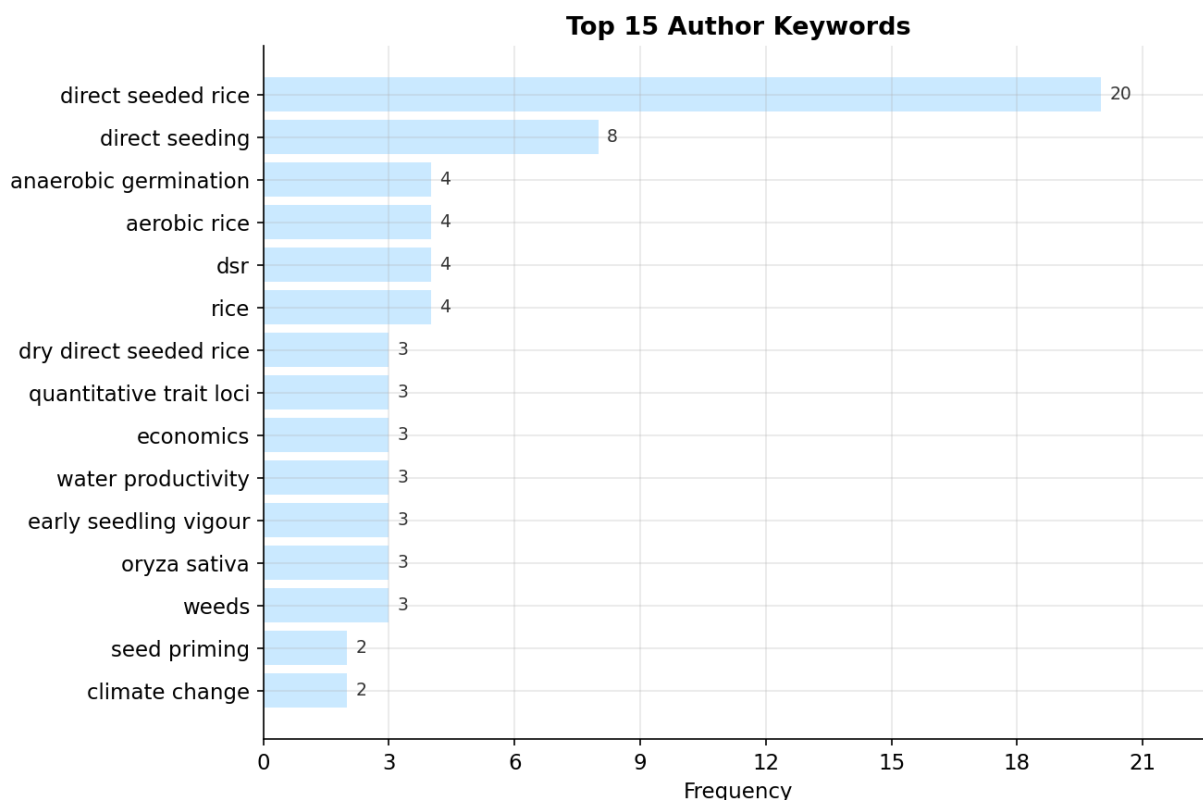


Fig. 8. Most frequent author keywords in the direct seeded rice research dataset.

The graph represents the frequency of the most used keywords by the author. The analysis shows that direct seeded rice (20 occurrences) and direct seeding (8 occurrences) are the most frequent terms. The following terms are anaerobic germination, aerobic rice, DSR and rice, each appearing 4 times, alongside early seedling vigour, quantitative trait loci, water productivity and weeds, each appearing 3 times. This keyword pattern aligns closely with the physiological traits examined in this review, confirming anaerobic germination tolerance, aerobic adaptation and early seedling vigour as research priorities within the DSR.

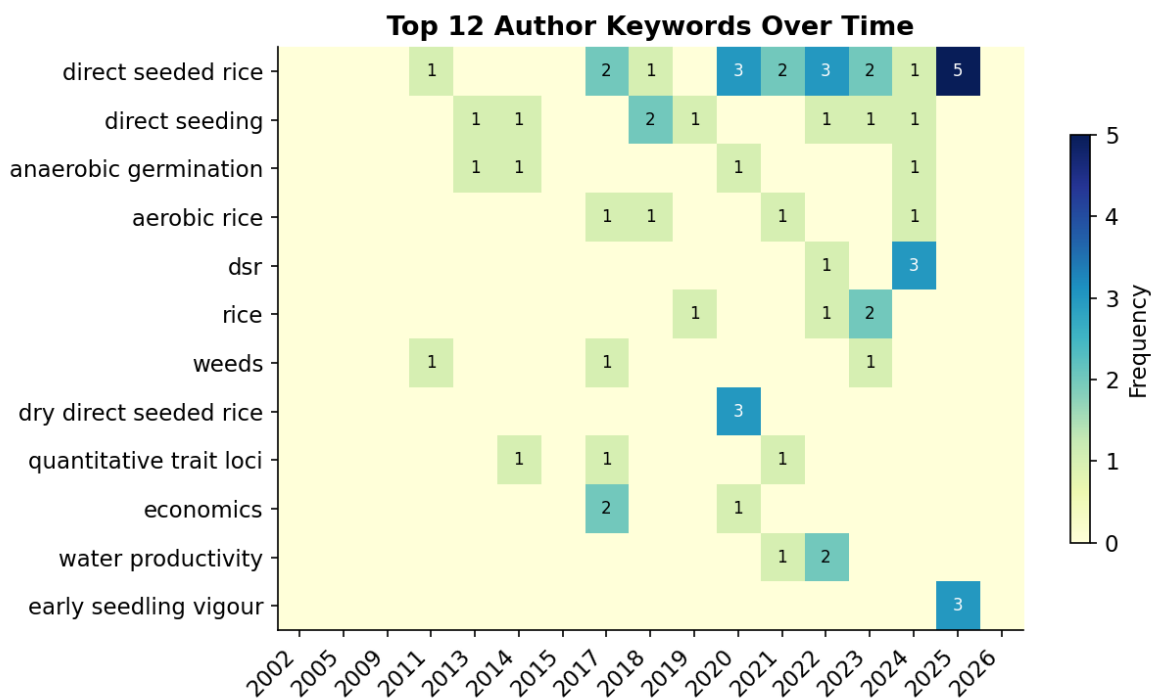


Fig. 9. Temporal distribution of major author keywords by author in the DSR research dataset.

The temporal keyword heatmap reveals a clear thematic shift in the DSR literature covered by this time. Early clusters (2011-2018) centered on weeds, quantitative trait loci and economics, reflecting an initial focus on agronomic feasibility and genetic mapping among the cited works. The mid-period shows diversification into dry direct -seeded rice and water productivity alongside sustained emphasis on direct -seeded rice. Notably, early seedling vigour emerges as a distinct new cluster in 2025, reaching a single-year frequency of 3, while direct -seeded rice has the highest single-year keyword frequency recorded in the dataset (5, in 2026). This recent emergence suggests early seedling vigour is gaining prominence among the works reviewed

9.CONCLUSION

Direct seeded rice can reduce labour and water requirements compared with transplanted rice, but its performance is strongly influenced by crop establishment, water availability, weed competition, nutrient supply and genotype × environment interactions. Physiological traits such as early seedling vigour, anerobic germination tolerance, photosynthetic performance, root-system architecture and nutrient-use efficiency contribute to adaptation to these conditions.

High-throughput phenotyping, physiological measurements, molecular approaches viz., QTL mapping, GWAS, marker-assisted selection and genomic selection provide complementary approaches for identifying and utilizing variation in these traits. Crop management practices, including appropriate seed treatment, integrated weed management, water management and balanced nutrient application remain important for improving DSR performance.

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