

RESEARCH ARTICLE

EVALUATION OF DIRECT SEEDED RICE AND ESTABLISHMENT METHODS OF RICE AND INTEGRATED WEED MANAGEMENT IN AUS, AMAN SEASON ACROSS DIVERS AGRO-ECOSYSTEMS IN BANGLADESH

Md. Ibrahim Ali^a, Sadid Md. Zaman^b, Nadira Akter Jothy^b, Mohammad Ferdous Ikbal^c, Motabber Rahman^d, Md. Mahamudul Hasan^a, Milon kobir^e, Md. Aktarul Islam^f, Israt Jahan Jany^g, Md.Tanjilur Rahman Mondal^h, M.S. Haqueⁱ, Sarkar M. J^a, Shams-Al-Mahmud^d, Md. Mahbulul Alam^j

^a Agronomy Division, BINA

^b Bangladesh Agricultural University

^c Plant Breeding Division, BINA

^d BINA Sub-station, Rangpur

^e BINA Sub-station Satkhira

^f Agricultural Engineering Division, BINA

^g DAM, District agricultural marketing office, Netrakona

^h Horticulture Division, BINA

ⁱ Plant Breeding Division, BINA

^j BINA Sub-station Ishwardi

*Corresponding Author Email: ibrahimbd402@gmail.com

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ABSTRACT

A series of field experiments were conducted across diverse agro-ecological zones of Bangladesh including drought prone areas Rajshahi and Chapainawabganj, flood affected deep water ecosystems Gopalganj and upland jhum systems in the Chottogram Hill Tracts to evaluate the performance of **Direct Seeded Rice (DSR)** relative to conventional puddled (PTR) and unpuddled transplanting (UPTR). Results demonstrated that PTR remains the most profitable and higher yield among establishment method under current management, with superior benefit cost ratios. UPTR provided intermediate performance, balancing water savings with acceptable yield levels, DSR generally recorded lower yields and profitability due to higher weed pressure, reduced straw yield and increased management costs. Field trials highlighted the potential of DSR when integrated with improved technologies and adapted genotypes. The deep water rice mutant line LD-200-1-3-3-4 achieved statistically higher grain yield (1.98 t ha⁻¹) under broadcasting in flood-prone Gopalganj and Binadhan-21 outperformed other aus rice genotypes in the jhum ecosystem under integrated management. Mechanized and precise planting at lower seed rate (20–25 kg ha⁻¹) demonstrate yield stability, the importance of precision seeding, land leveling and seed treatment. Integrated weed management strategies, site-specific nutrient management and irrigation scheduling tools were identified as critical interventions to overcome the major constraints of DSR, particularly weed infestation. Collectively, the findings suggest that DSR method faces agronomic and economic limitation, it holds considerable promise as a resource conserving, climate resilient and labor-saving technology. The future of DSR in Bangladesh lies in genotype, management and environment integration, ensuring that the system economically viable and environmentally sustainable alternative to conventional rice establishment methods.

KEYWORDS

DSR, Aus Rice, Weed

1. INTRODUCTION

Rice constitutes the principal staple food of Bangladesh and exerts a profound influence on national food demand, economic development and social stability. The crop occupies more than 80% of the total gross cropped area, its dominance in the agricultural landscape. Rice provides over one fourth of the total caloric intake of the population. Rice cultivation contributes substantially to gross domestic product (GDP) through direct agricultural output and indirect with agro industries, rural employment and trade. Rice availability is directly correlated with food security, as fluctuations in production translate into variations and nutritional adequacy. Rice farming plays a pivotal role in poverty

alleviation by generating income opportunities for smallholder farmers, landless laborers and women engaged in post harvest processing. The sustainability of rice production is not only agronomic concern but also a critical determinant of Bangladesh's economic resilience, nutritional well-being and progress toward poverty reduction. Rice productivity fluctuates by climatic variability, soil fertility decline, resource constraints has cascading effects on food security, national economy and social equity. Integrated Weed Management in DSR shows promising potential for sustainable rice production across diverse agro-ecosystems in Bangladesh, with significant yield stability and cost reduction strategies (Bhuiyan et al., 2021). By increasing seeding rates in direct seeded rice can suppress weed growth and improve crop yields,

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particularly under partially weedy conditions, as evidenced by experiments conducted in the Aman season in Bangladesh over two years (Ahmed et al., 2014). Integrated weed management strategies can reduce yield loss and increase rice production by up to 0.43 million tons by 2030, with specific critical periods for weed control in Aus, T. Aman and Boro seasons (Bhuiyan et al., 2020). Integrated weed management strategies using weed-competitive rice cultivars and high seeding rates improve rice yield under dry direct-seeded conditions, with significant interactions between weeding regimes, cultivars and seeding rates (Ahmed et al., 2021). Direct seeding of rice increases yield compared to traditional transplanting with effective weed management using oxadiazon and manual weeding, supported by three-year agronomic studies and socio-economic evaluation (Mazid et al., 2003). Direct-seeded rice faces challenges of significant yield loss due to weed infestation; integrated weed management practices such as co-culture with *Sesbania* and specific herbicide combinations can effectively reduce weed populations and increase yield in zero-till rice-wheat systems (Ghosh et al., 2017). Integrated weed management strategies are crucial for sustainable direct seeded rice, with a need for less herbicide and environmentally friendly methods (Juraimi et al., 2013). Integrated weed management combining cultural, mechanical, biological and chemical methods is recommended for sustainable control in Direct Seeded Rice systems, emphasizing the need for an integrated approach for effective and sustainable weed control (Vairamuthu et al., 2025). Direct seeded rice with integrated weed management using herbicides and hand weeding, combined with specific fertilizer rates, significantly improves grain yield and reduces production costs in dry seasons (Shultana et al., 2016). Dry seeding of rice in Bangladesh's Barind Tract allows for earlier establishment and reduces drought impact, but early season weed growth is a major constraint and on-farm studies show yield gaps due to weed management issues, with integrated practices like pre-emergence herbicides and inter-row weeding showing promise (Mazid et al., 2001). Direct seeded rice offers advantages over traditional flooded rice cultivation, including reduced labor and water use, but faces challenges with weed management is critical for its success (Nagargade et al., 2018). Direct-seeded rice faces significant weed-related losses; integrated weed management strategies involving stale seed beds, herbicides and mulching are effective; specific rice cultivars and chemical management strategies are recommended (Singh et al., 2016). Direct Seeded Rice is becoming popular due to its low-input demands and potential for sustainability, but faces challenges by high weed infestation pressure (Joshi et al., 2013). The effective and economic weed management is crucial for sustainable rice production and ecological management involves integrated strategies to shift the crop-weed balance in favor of rice (Rao et al., 2011). The integration of chemical and manual weed management use of Topstar® 400 SP @ 190 mL ha⁻¹ combined with one hand weeding at 25 DAT provided the most effective and economical weed control strategy, ensuring maximum yield benefits. Sole application of Sunrice 13.75 WG also showed promising results among herbicide treatments, though combined approaches proved superior (Hasanuzzaman et al., 2009). Integrated weed management strategies that combine pre-emergence and post-emergence herbicides have demonstrated both effectiveness and cost-efficiency in direct-seeded rice systems. A research findings shows that sequential application of pendimethalin followed by bispyribac-sodium achieved up to 85% weed control in field trials conducted in Nepal (Dhakal et al., 2019). bispyribac sodium, a post emergence herbicide belonging to the pyrimidinyl carboxy herbicide group, has been widely studied for its efficacy in direct-seeded rice systems. At an application rate @ 25 g ha⁻¹, it has been reported to provide effective control of a broad spectrum of grassy and broadleaf weeds, thereby improving crop establishment and yield performance. A study from India during the 2019 rainy season to evaluate the performance of bispyribac sodium under both rainfed and irrigated agro-ecosystems. The findings demonstrated that the herbicide significantly reduced weed density and biomass, leading to enhanced crop growth and yield attributes. The highest growth and yield responses were observed under irrigated conditions, highlighting the synergistic effect of adequate water availability and chemical weed management (Verma et al., 2023).

1.1 Direct seeded rice: a more sustainable approach to rice production

The demand for rice is on the rise to meet the food security of emerging population. Projections by the International Rice Research Institute (IRRI) anticipate rice production needs to increase by 25% in the next 25 years in order to meet global demand. To achieve this challenge in a sustainable way, we have to produce this extra rice more efficiently with

less labor, water, energy and agro-chemicals to reduce the environmental footprint of rice production. In traditional rice cultivation methods, 40% of the world's irrigation water is applied for rice production. Increasing water scarcity due to climate change and competition from urbanization is making this traditional method of rice production unsustainable in the long term. Due to shortage of labor and decreasing arable land, innovations in rice cultivation are critically needed to meet rising demand and ensure food security. One of the potential solutions to address these challenges is direct seeded rice. Direct seeding is a crop establishment system where in rice seeds are sown directly into the field, as opposed to the traditional method of growing seedlings in a nursery, then transplanting into flooded fields. Direct seeded rice is seen to be one of the most efficient, sustainable and economically viable rice production systems. Puddled transplanting method preferable but DSR delivers faster planting and maturing, conserves scarce resources like water and labor, is more conducive to mechanization and reduces emissions of greenhouse gases that contribute to climate change. Mechanized DSR also creates avenues for employment through new service provisions and is less labor intensive, hence more attractive to youth and women farmers. Although direct seeding is widely practiced in the United States and South America, productivity challenges have limited its wide-scale adoption in Asia, where 90% of the global rice is produced and consumed. An integrated and scientific approach to make direct seeded rice socioeconomically and environmentally sustainable.

1.2 Advantages of direct seeding

Savings on irrigation water by 12-35% under efficient water management practices. Reduces labor by eliminating seedling uprooting and transplanting to the main field. Reduces cultivation time, energy and cost, no plant stress from transplanting shock. Faster maturation of crops, lower GHG emissions. Mechanized DSR provides employment opportunities for youth through service provision business model. Increases total income by reducing cost of cultivation. Higher seed rates, seeds exposed to birds and pests, seed management cost higher. Higher risk of lodging risk of poor crop establishment rates. These Issues associated with DSR and potential opportunities for DSRC to contribute in realizing the full potential of DSR technology for major rice growing nations. Risk of poor and uneven crop stand if field get inundation during early germination/emergence phase due to rain or poor leveling. To evaluate the performance of anaerobic germination tolerant rice in reducing the risk of seedling mortality due to early field inundation caused by rain or due to poor leveling of fields.

2. MECHANIZED AND PRECISE PLANTING WITH LOW SEED RATE IN DIRECT-SEEDED RICE

Direct-seeded rice represents a transformative approach to rice cultivation, offering potential reductions in labor, water use and production costs compared to conventional puddled transplanted systems. A critical component of successful DSR is the adoption of mechanized and precision planting technologies that enable uniform seed distribution, optimal plant population density and efficient resource utilization. Recent agronomic evidence indicates that robust yields can be achieved in mechanized DSR systems with significantly reduced seed rates. Trials conducted in Bangladesh, India, China, and Cambodia demonstrate that seed rates of 20–25 kg ha⁻¹ were sufficient to establish optimal plant stands when precision planting equipment was employed. Traditional broadcasting methods require 40–60 kg ha⁻¹ to compensate for uneven germination and less plant establishment.

2.1 Technological Interventions

Mechanized seed drills and planters ensure uniform seed depth and spacing, reducing intra-specific competition and enhancing tillering capacity. Laser assisted land leveling improves water distribution and seedling emergence, stabilizing plant populations under DSR. Use of fungicides, insecticides and growth regulators to seed prior to sowing enhances germination, seedling vigor and resilience to biotic and abiotic stress. Lower seed rates facilitate the use of high-quality hybrid and inbred cultivars, maximizing genetic potential and yield stability. Mechanized DSR with low seed rates has consistently achieved high yields comparable to or exceeding transplanted rice systems, while reducing input costs. Optimized planting density enhances nitrogen use efficiency and reduces lodging risk. Adoption of mechanized DSR contributes to sustainability goals by lowering water demand, minimizing methane emissions, and reducing labor dependency. Mechanized and precise planting with low seed rates constitutes a scientifically validated

strategy for advancing DSR systems across rice growing countries. By integrating precision technologies with improved seed management practices, farmers can achieve high productivity while adapting to local agro-ecological conditions. This approach aligns with broader objectives of resource conservation, climate resilience and food security in rice dependent economies.

2.2 Weed Management in Direct-Seeded Rice

Direct-seeded rice systems are highly vulnerable to weed infestation due to the absence of standing water during the critical establishment phase. Key issues include, high weed pressure leading to yield losses of up to 60–90% if unmanaged. Evolution of herbicide resistance in major weed species due to repeated use of single mode of action herbicides. Shift in weed flora toward difficult to control species such as *weedy rice*, *Echinochloa crus-galli* and *Cyperus rotundus*. Poor herbicide efficacy resulting from suboptimal application technologies and lack of precision in spray delivery.

2.3 Integrated Weed Management Strategies

An integrated approach is required that integrates chemical, mechanical, biological and cultural practices. Deployment of herbicide tolerant rice cultivars combined with stewardship programs. Rotational use of herbicides with different modes of action to delay resistance evolution. Genetic and molecular tools for early detection of resistant biotypes. Development of ICT based platforms and mobile apps for site specific herbicide recommendations. Integration of weed population dynamics models to predict infestation risk and guide management timing. Screening of novel broad-spectrum herbicides with dual or multiple modes of action. Use of nano-formulations and encapsulated herbicides to improve persistence and reduce environmental hazard. Utilization of anaerobic germination tolerant rice cultivars that establish under saturated conditions that suppress weed emergence. Breeding for early vigor, rapid canopy closure and allelopathic potential to enhance crop competitiveness. Precision mechanical weeders (e.g., rotary weeders, inter-row cultivators) adapted for DSR. Mulching and cover crops to reduce weed seed germination. Crop rotation with legumes or non-rice cereals to break weed cycles. Drone based spraying and sensor-guided applicators for uniform coverage. Training programs for farmers on safe herbicide handling and calibration of sprayers. Integration of herbicide application with fertigation systems in micro irrigation setups.

2.4 Water and Nutrient Management

DSR methods requires tailored irrigation scheduling tools to optimize water use while suppressing weed growth. Sprinkler and drip systems can be refined to deliver water and nutrients precisely, reducing weed proliferation and enhancing fertilizer use efficiency. Adoption of Site-Specific Nutrient Management, use of slow and controlled release fertilizers to synchronize nutrient availability with crop demand. Addressing micronutrient deficiencies (Fe, Zn) through fortified formulations. Strategies to minimize greenhouse gas emissions (N_2O , CH_4) by integrating water and nutrient management. Most rice cultivars currently used are bred for transplanted conditions. To realize the full potential of DSR, cultivars must be identified and tested for traits such as: anaerobic germination tolerance, early vigor with rapid and uniform emergence, weed competitiveness through canopy architecture, shorter duration with high yield potential, lodging resistance under dry conditions.

3. MATERIALS AND METHODS

Field experiments were conducted across multiple agro-ecosystems of Bangladesh between 2017 and 2021. Experiments on establishment methods and herbicide treatments were carried out under rainfed and irrigated conditions aus season during 2020–2021. Comparative assessments of establishment and tillage methods were conducted in drought-prone districts of Rajshahi and Chapainawabganj in aman season during 2017–2018. Direct-seeded *aus* rice genotypes were evaluated in the upland rainfed conditions of the Chottogram Hill Tracts Jhum ecosystem in 2020–2021. Mutant lines were tested under broadcasting in flood-prone areas of Gopalganj deep-water rice in aman season during 2020–2021. Four establishment methods broadcasting, line sowing, dibbling and transplanting were compared using a randomized complete block design with three replications during aus season 2020–2021. Direct-seeded aus rice plots were treated with three herbicide

combinations, including Bensulfuron methyl + Acetachlor, in a RCBD with three replications of herbicide evaluation during 2020–2021. Three establishment methods direct-seeded rice (DSR), puddled transplanting (PTR) and unpuddled transplanting (UPTR) were tested using a split-plot design with establishment methods as main plots and genotypes as subplots of aman rice establishment during 2017–2018. Three aus rice genotypes were evaluated under integrated management practices using RCBD with three replications Jhum ecosystem trials during 2020–2021. Mutant lines were evaluated under broadcasting method at a seed rate @ 22.5 kg ha^{-1} using RCBD with three replications deep-water rice mutants during 2020–2021. Fields were prepared according to local practices, including plowing, harrowing and leveling. Nutrient management followed site-specific nutrient management principles, with recommended doses of N, P, K and micronutrients applied. Manual weeding was performed at 25 and 50 days after transplanting (DAT) in relevant treatments. Herbicides were applied at recommended doses using knapsack sprayers. Irrigated plots were maintained under saturated conditions. Rainfed and jhum plots relied on natural rainfall. Deep-water rice plots were managed under prolonged submergence conditions. Plant height, tiller number, panicle number, and grain yield were recorded at maturity. Expenditure, gross income, net profit, and benefit cost ratio (BCR) were calculated for each treatment. Data were subjected to analysis of variance (ANOVA) using appropriate statistical software. Treatment means were compared using least significant difference (LSD) at 5% probability level (Gomez and Gomez, 1984).

4. RESULTS

4.1 Evaluation of Different Establishment Methods and Yield of Aus Rice during 2020–2021

The comparative assessment of four establishment methods broadcasting, line sowing, dibbling, and transplanting during the Aus season of 2020–2021 revealed significant differences in yield and economic performance. Transplanting recorded the highest yield and profitability, with an expenditure of Tk. 136,182 ha^{-1} , gross income of Tk. 218,290 ha^{-1} and net profit of Tk. 82,108 ha^{-1} . The benefit cost ratio (BCR) was 1:1.60, the most favorable among all methods. Line sowing achieved intermediate performance, with a profit of Tk. 67,120 ha^{-1} and a BCR of 1:1.48, reflecting its potential as a structured dry-seeded method with better plant population management. Dibbling produced comparable income Tk. 212,078 ha^{-1} but required higher expenditure Tk. 158,260 ha^{-1} , resulting in a lower profit Tk. 67,138 ha^{-1} and BCR (1:1.34). Broadcasting showed the lowest economic efficiency, with a profit of Tk. 53,585 ha^{-1} and a BCR of 1:1.39, largely due to uneven crop establishment and higher weed competition. Transplanting remains the most productive and economically viable establishment method for Aus rice, while line sowing and dibbling offer moderate alternatives. Broadcasting is a simple and labor-saving, was the least efficient in terms of yield and profitability.

4.2 Evaluation of Herbicide Treatments on Weed Management and Yield of Aus Rice during 2020–2021

The effect of different herbicide treatments under direct-seeded Aus rice was evaluated to determine their impact on weed suppression and yield performance. Among the three treatment combinations tested, the plot treated with Bensulfuron methyl + Acetachlor produced the highest grain yield, demonstrating superior efficacy in controlling both broadleaf and grassy weeds. Other herbicide treatments showed moderate effectiveness, but yield levels were consistently lower compared to the Bensulfuron methyl + Acetachlor combinations. The results highlights the integrated herbicide use is critical for successful direct-seeded Aus rice, as weed infestation remains the primary constraint to yield stability. The experiments confirm that transplanting is the most profitable establishment method for Aus rice, while line sowing and dibbling provide intermediate options. Broadcasting, although labor-efficient, is constrained by poor crop establishment and weed pressure. In direct-seeded systems, Bensulfuron methyl + Acetachlor was the most effective herbicide treatment, delivering the highest yield by ensuring broad-spectrum weed control. These findings underscore the importance of combining appropriate establishment methods with effective weed management strategies to optimize Aus rice productivity in Bangladesh. Out of four rice establishment methods (broadcasting, line sowing, dibbling and transplanting), transplanting method produce the highest yield.

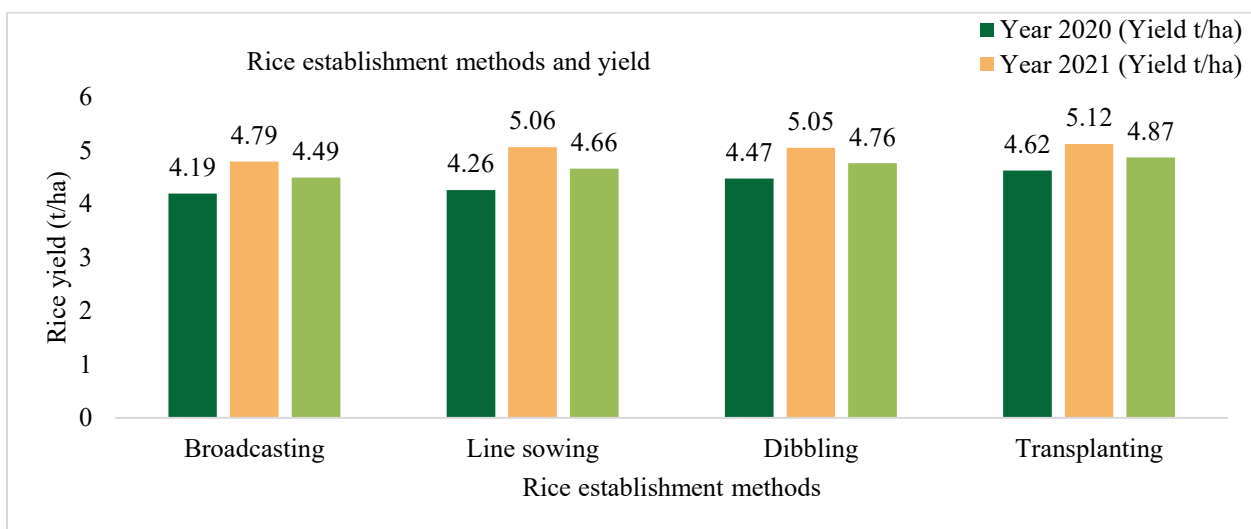


Figure 1: Performance of different establishment methods during 2020-2021

Table 1: Benefit cost ratio of different rice establishment methods				
Establishment methods	Expenditure (tk/ha)	Income (tk/ha)	Profit (tk/ha)	BCR
Broadcasting	143922	200467	53585	1:1.39
Line sowing	142140	209260	67120	1:1.48
Dibbling	158260	212078	67138	1:1.34
Transplanting	136182	218290	82108	1:1.60

4.3 Evaluation of different establishment method and effect of different herbicide on weed management and yield of Aus rice

Out of three treatment combination from herbicide treated (Bensulfuron methyl+Acetachlor) plot gave the highest yield.

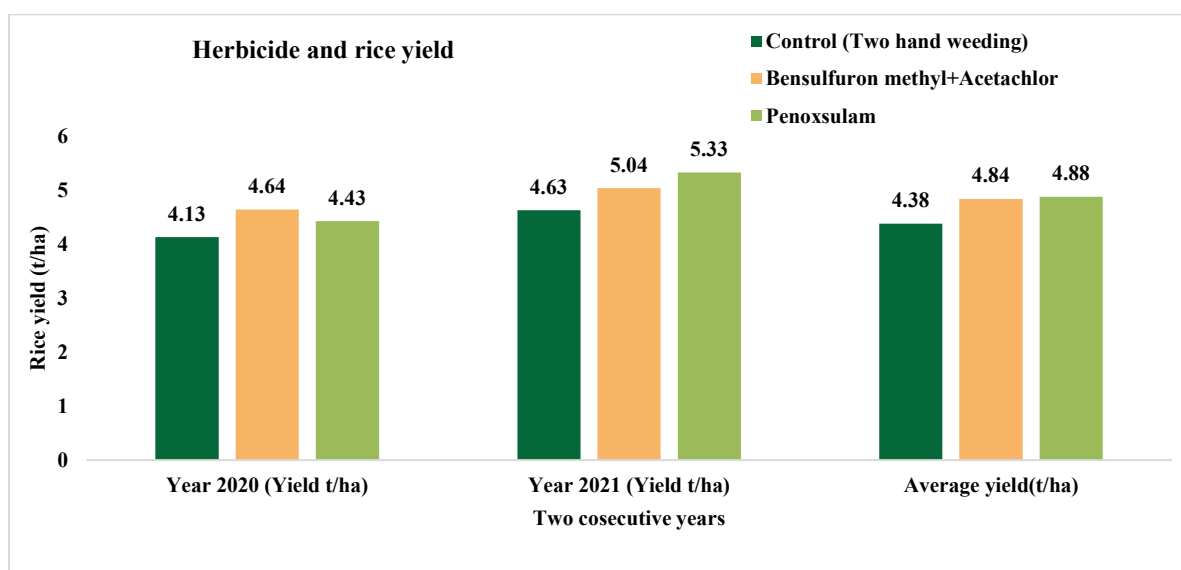


Figure 2: Performance of different herbicide under direct seeded rice in Aus season during 2020-2021

4.4 Evaluation of different establishment method and yield of Aman rice in drought prone region in Rajshahi and Chapainawabganj

A comparative assessment of rice establishment methods during the Aman seasons of 2017 and 2018 in the drought-prone regions of Rajshahi and Chapainawabganj revealed differences in both yield performance and economic returns. Among the three methods evaluated direct-seeded rice (DSR), puddled transplanting (PTR) and unpuddled transplanting (UPTR). PTR consistently delivered the highest grain yield, averaging 5.45 t ha⁻¹ across the two years. This was followed by UPTR at 5.305 t ha⁻¹, while DSR recorded the lowest average yield of 5.215 t ha⁻¹. The yield advantage of PTR is attributed to better weed suppression and more stable crop establishment under saturated conditions. Economic analysis further reinforced the superiority of PTR, which incurred the lowest

production cost (Tk. 85,290 ha⁻¹) and generated the highest income (Tk. 139,330 ha⁻¹), resulting in a net profit of Tk. 54,040 ha⁻¹ and a benefit-cost ratio (BCR) of 1:1.63. UPTR offered moderate profitability with a net return of Tk. 44,490 ha⁻¹ and a BCR of 1:1.48, balancing water savings with acceptable yield performance. In contrast, DSR, despite its potential for reducing water and labor inputs, showed the lowest profitability (Tk. 31,689 ha⁻¹) and BCR (1:1.32), primarily due to increased weed management costs and reduced yield stability under dry field conditions. PTR remains the most economically viable method under current situation, UPTR presents a promising alternative in water-scarce environments. DSR, though less profitable at present, holds potential for future adoption if integrated with improved weed control strategies, precision seeding technologies and cultivars specifically adapted to dry-seeded systems.

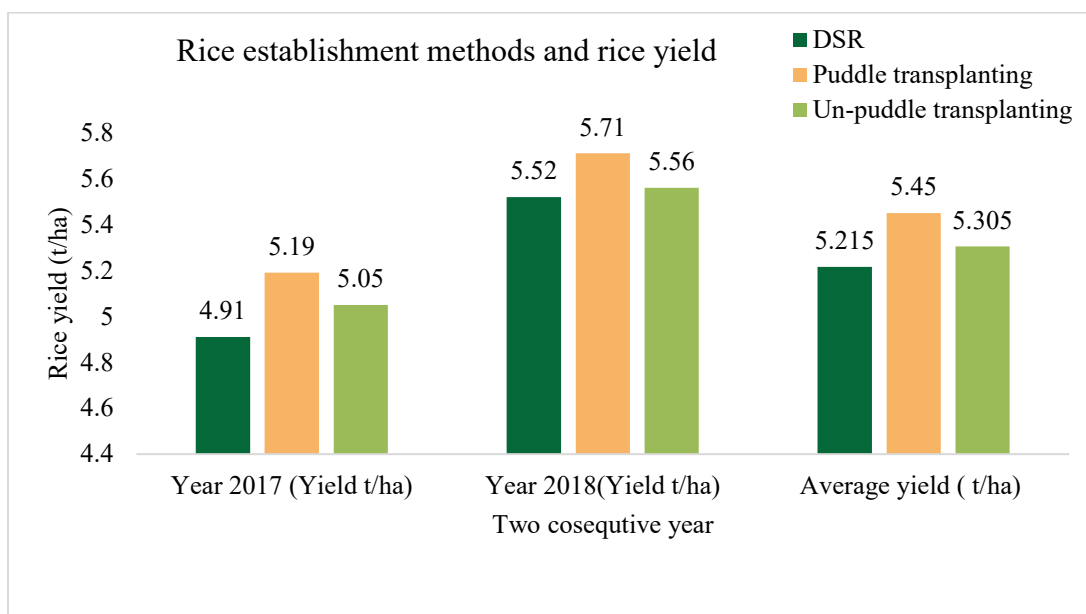


Figure 3: Performance of different establishment methods in Aman season during 2017 and 2018 in drought prone regions (Rajshahi and Chapainawabganj)

The comparative performance of different rice establishment methods during the Aman seasons of 2017 and 2018 in drought-prone regions of Rajshahi and Chapainawabganj revealed significant differences in economic returns and benefit-cost ratios (BCR).

Direct-Seeded Rice (DSR): The average expenditure under DSR was Tk. 96,543 ha⁻¹, which was higher than puddled transplanting but slightly above unpuddled transplanting. Gross income was Tk. 128,232 ha⁻¹, resulting in a net profit of Tk. 31,689 ha⁻¹. The BCR was 1:1.32, indicating relatively lower profitability compared to transplanting methods. The reduced profitability is attributed to higher weed management costs, lower yield stability, and reduced straw yield under dry-seeded conditions.

Puddled ransplanting (PTR): PTR recorded the lowest expenditure (Tk. 85,290 ha⁻¹) among the three methods. Gross income was the highest at Tk. 139,330 ha⁻¹, leading to a net profit of Tk. 54,040 ha⁻¹. The BCR was 1:1.63, the highest among all establishment methods, demonstrating superior economic efficiency. The higher profitability of PTR is linked to

better weed suppression due to standing water, higher grain and straw yields and reduced input costs for weed control.

Unpuddled Transplanting (UPTR): Expenditure under UPTR was Tk. 91,230 ha⁻¹, intermediate between DSR and PTR. Gross income reached Tk. 135,720 ha⁻¹, resulting in a profit of Tk. 44,490 ha⁻¹. The BCR was 1:1.48, higher than DSR but lower than PTR. UPTR offered moderate profitability, benefiting from reduced water use compared to PTR, but still maintaining better yield stability than DSR. Profitability of PTR > UPTR > DSR. PTR had the lowest expenditure and highest returns, while DSR incurred higher costs with lower net profit. PTR achieved the most favorable BCR (1:1.63), followed by UPTR (1:1.48), and DSR (1:1.32). PTR remains the most economically viable method in drought-prone regions, despite its higher water requirement. UPTR offers a compromise between water saving and profitability, making it suitable where water scarcity is moderate. DSR, while reducing water demand and labor requirements, suffers from lower profitability due to weed pressure and yield penalties, highlighting the need for improved weed management and cultivar adaptation.

Table 2: Performance of different establishment methods in Aman season during 2017 and 2018 in drought prone regions (Rajshahi and Chapainawabganj)

Establishment methods	Expenditure (tk/ha)	Income (tk/ha)	Profit (tk/ha)	BCR
Direct seeded rice	96543	128232	31689	1:1.32
Puddle transplanting	85290	139330	54040	1:1.63
Unpuddle transplanting	91230	135720	44490	1:1.48

4.5 Evaluation of different tillage method and yield of Aman rice in drought prone region in Rajshahi and Chapainawabganj

The evaluation of three tillage methods direct seeded rice (DSR), puddled transplanting (PTR), and unpuddled transplanting (UPTR) during the Aman seasons in drought-prone districts of Rajshahi and Chapainawabganj revealed clear differences in yield performance and economic efficiency. Across two consecutive years, puddled transplanting consistently produced the highest grain yields compared to DSR and UPTR. Average yields under PTR exceeded 5.4 t ha⁻¹, while UPTR achieved intermediate yields of approximately 5.3 t ha⁻¹. DSR recorded the lowest average yield at around 5.2 t ha⁻¹. The superior performance of PTR is attributed to better crop establishment, improved weed suppression under saturated soil conditions, and enhanced nutrient uptake efficiency. Economic analysis further confirmed the advantage of PTR. It required the lowest production expenditure while generating the highest gross income, resulting in a net profit of more than Tk. 54,000 ha⁻¹ and a benefit cost ratio (BCR) of 1:1.63. UPTR provided moderate profitability with a BCR of 1:1.48, reflecting its potential as a water saving alternative with acceptable yield stability. DSR, although reducing water

and labor requirements, showed the lowest profitability (BCR 1:1.32) due to higher weed management costs and reduced yield stability under dry field conditions. The figure on genotype performance highlights that varietal differences also played a significant role in determining yield outcomes under drought-prone conditions. Certain genotypes demonstrated resilience and maintained yield stability across establishment methods, while others were more sensitive to tillage practices. In particular, drought tolerant local cultivars and improved lines adapted to dry seeded conditions showed promise in sustaining productivity under DSR and UPTR systems. The results clearly demonstrate that puddled transplanting remains the most productive and economically viable tillage method in drought prone regions of Bangladesh. However, unpuddled transplanting offers a practical compromise, balancing water conservation with yield stability. Direct seeded rice, while less profitable under current management practices, holds potential for future adoption if integrated with improved weed control, precision seeding technologies, and cultivars specifically bred for dry-seeded environments. Out of three tillage methods (direct seeded rice, puddled transplanting, unpuddle transplanting) from puddle transplanting the highest yield and BCR found.

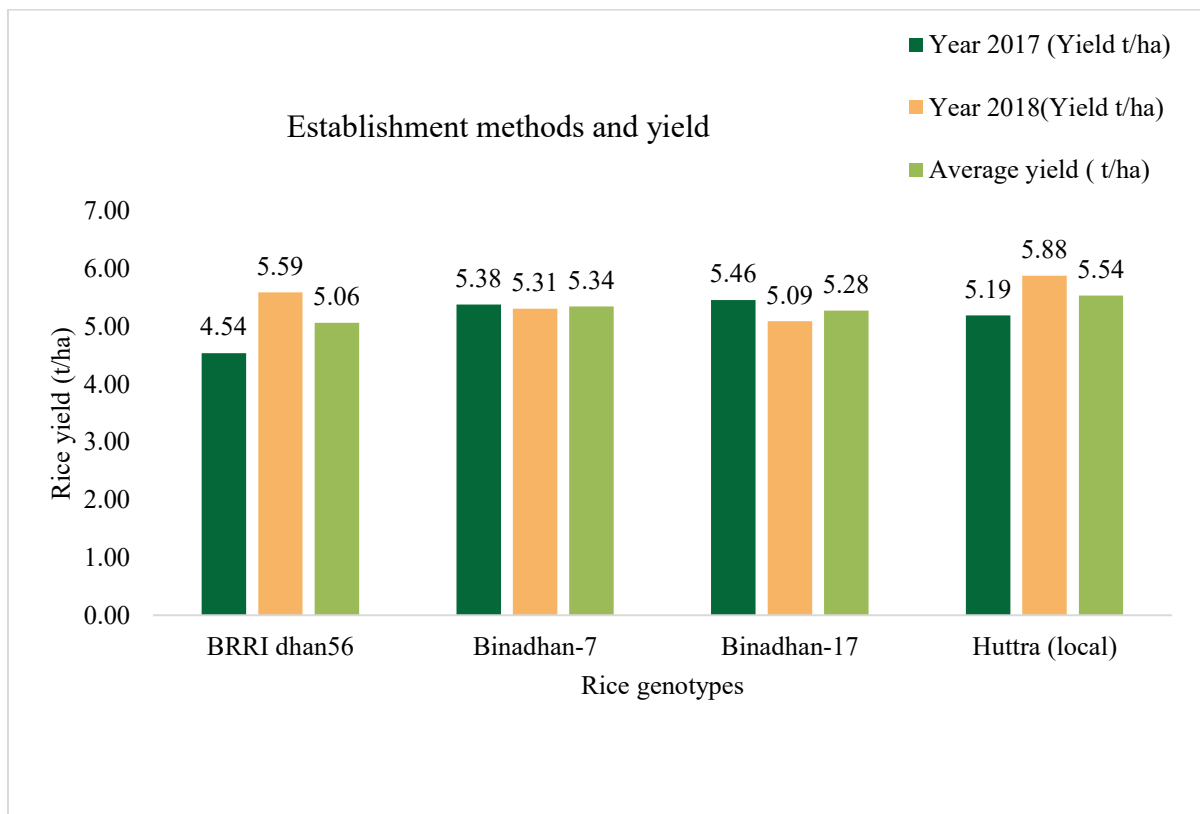


Figure 4 : Performance of different genotypes in drought prone regions in Bangladesh during Aman season

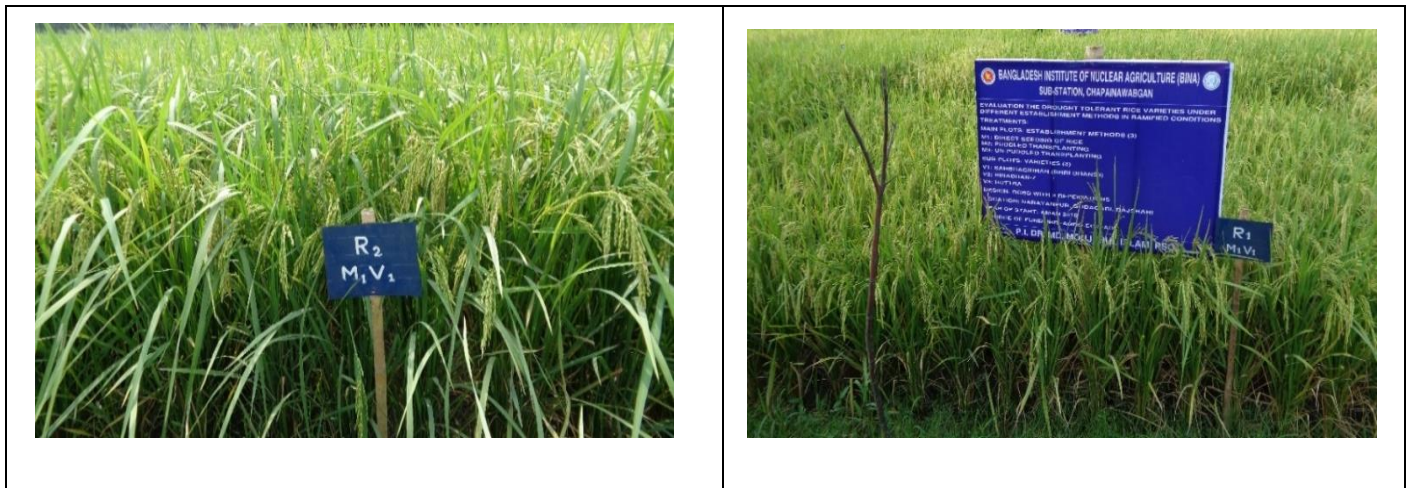


Figure 5 : Aman rice in drought prone region (Rajshahi and Chapainawabganj)

4.6 Evaluation of DSR aus rice mutants/genotypes and yield through integrated management in jhum ecosystem

The evaluation of direct seeded aus rice mutants/genotypes under integrated management practices in the jhum ecosystem of the Chottogram Hill Tracts revealed significant variation in yield performance. Out of the three genotypes assessed, Binadhan-21 consistently produced the highest grain yield, demonstrating superior adaptability to the upland, rainfed conditions typical of jhum cultivation. Binadhan-21 outperformed the other tested genotypes across both years, indicating its resilience under the challenging condition of the hill tracts. The higher yield potential of Binadhan-21 is attributed to its early vigor, tolerance to intermittent drought stress and competitive ability against upland weeds. Several genotypes showed moderate to lower yields, reflecting variability in adaptation to the jhum ecosystem's unique constraints, including shallow soils, irregular rainfall and high weed pressure. The adoption of integrated management practices such as precise seed placement, improved land preparation and site-specific nutrient management contributed to better crop establishment and enhanced yield stability. Weed management was particularly critical, as upland weeds pose a major constraint in dry seeded systems. Mechanical

weeding combined with selective herbicide use improved crop competitiveness. Fertilizer application following site-specific nutrient management principles enhanced nutrient use efficiency, reducing both input costs and environmental losses. Performance data from 2020 and 2021 confirmed the stability of Binadhan-21 under variable rainfall conditions, reinforcing its suitability for scaling in jhum areas. Yield fluctuations in other genotypes highlighted the importance of genotype × environment interactions, suggesting that broader testing across seasons and micro environment is necessary before large-scale dissemination. The results demonstrate that Binadhan-21 is the most promising aus rice genotype for direct seeding in the jhum ecosystem of the Chottogram Hill Tracts, combining high yield potential with adaptability to upland conditions. Integrated management practices further enhanced its performance, underscoring the need for holistic approaches that address weed control, nutrient management, and crop establishment. While other genotypes showed moderate performance, their variability suggests limited suitability under current jhum conditions. Future research should focus on expanding the genetic base of aus rice for upland systems, integrating traits such as drought tolerance, weed competitiveness and nutrient efficiency. In Chottogram hill tracts out of three genotypes from Binadhan-21 the highest yield was obtained.

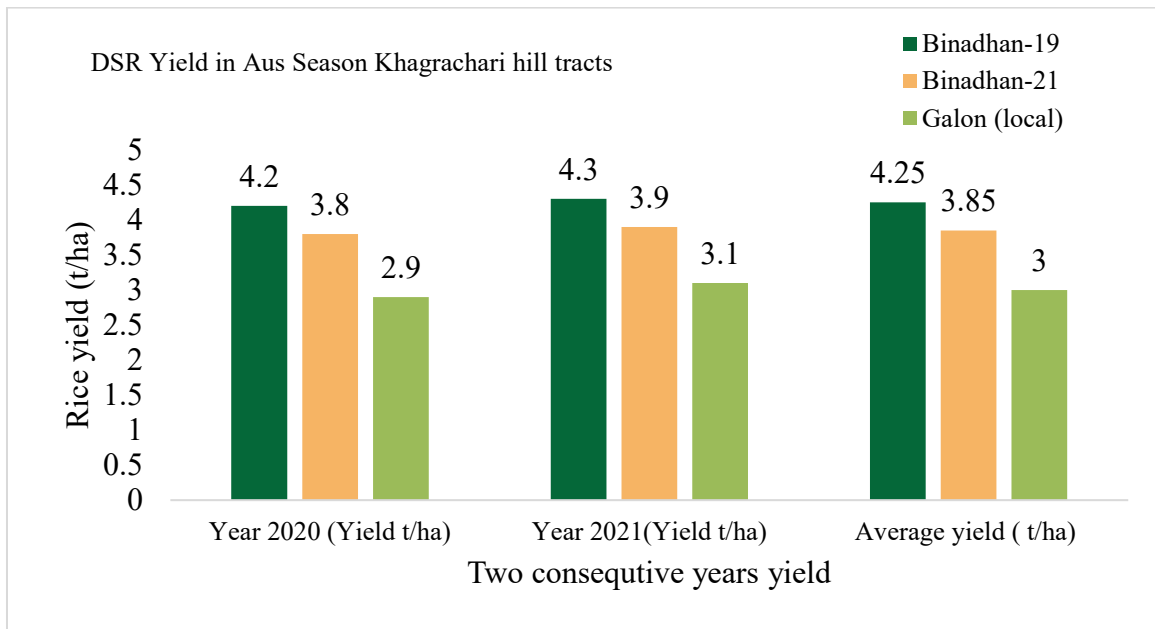


Figure 6: Performance of DSR aus rice mutants/genotypes and yield through integrated management in jhum ecosystem during 2020 and 2021

4.7 Evaluation of advance deep water rice mutant under broadcasting method in Gopalganj during Aman season



Figure 7: The evaluation of advanced deep water rice mutant lines under the broadcasting method during the Aman season in Gopalganj.

The evaluation of advanced deep water rice mutant lines under the broadcasting method during the Aman season in Gopalganj, a flood prone district of Bangladesh, revealed significant differences in yield performance. Among the tested lines, the mutant LD-200-1-3-3-4 produced the highest grain yield of 1.98 t ha^{-1} when sown at a seed rate of 22.5 kg ha^{-1} . Statistical analysis confirmed that this yield was significantly higher compared to other mutant lines evaluated under the same conditions. LD-200-1-3-3-4 demonstrated superior adaptability to deep water conditions, maintaining stable establishment and grain filling despite prolonged submergence. The broadcasting method proved effective in ensuring uniform crop stand in inundated fields, where transplanting is often impractical. Other mutant lines showed comparatively lower yields, highlighting the genetic advantage of LD-200-1-3-3-4 under flood affected ecosystems. The broadcasting method facilitated rapid seedling establishment, which is critical in deep

water environments where early vigor determines survival. LD-200-1-3-3-4 exhibited strong culm elongation ability, allowing the crop to escape submergence and sustain photosynthetic activity. The seed rate of 22.5 kg ha^{-1} was found to be optimal, balancing plant density with resource availability and minimizing competition. The statistically higher yield of LD-200-1-3-3-4 under broadcasting suggests its potential for large-scale adoption in flood prone areas of Gopalganj and similar ecosystems. Broadcasting offers a practical and low-cost establishment method for deep water rice, reducing labor requirements compared to transplanting. The performance of LD-200-1-3-3-4 highlights the importance of breeding and selecting genotypes specifically adapted to deep water conditions, ensuring food security in vulnerable regions. The deep water rice mutant line, LD-200-1-3-3-4 produced statistically higher grain yield (1.98 t ha^{-1}) under broadcasting method, seed rate at 22.5 kg ha^{-1} in Gopalganj.

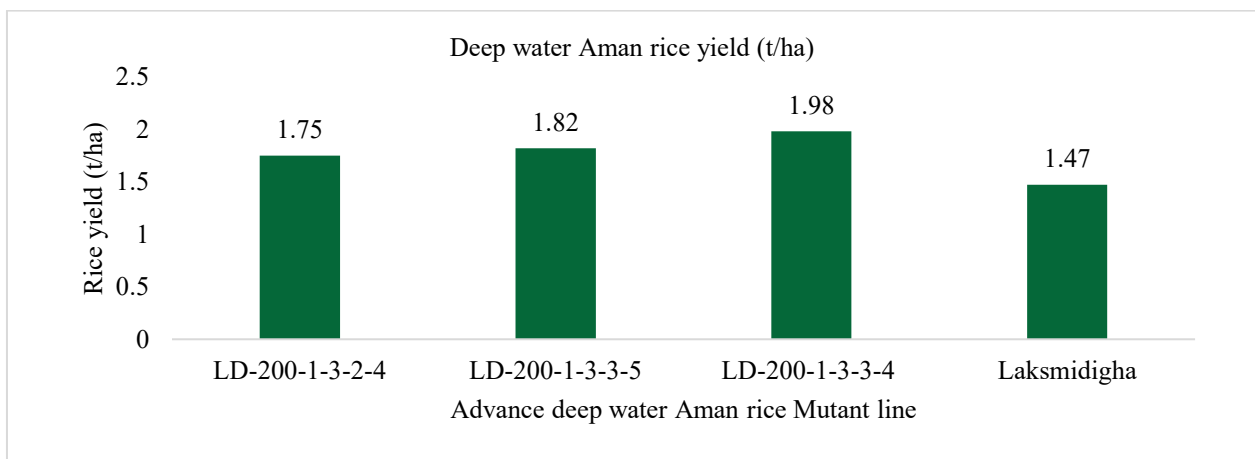


Figure 8: Performance of deep water rice mutant under broadcasting method in Gopalganj during Aman season

5. DISCUSSIONS

The comparison of DSR, puddled transplanting (PTR) and unpuddled transplanting (UPTR) revealed that PTR remains the most profitable and highest yielding method under drought prone conditions. Its advantage stems from better weed suppression due to standing water and more stable crop establishment. UPTR provided intermediate performance, balancing water savings with acceptable yield levels, while DSR suffered yield penalties and lower benefit-cost ratios because of high weed pressure and increased management costs. These findings highlight that while PTR is still dominant, UPTR offers a transitional option in water scarce regions and DSR requires improved weed management and cultivar adaptation to become competitive.

5.1 Mechanized and Precise Planting with Low Seed Rate in DSR

Trials in Bangladesh, India, China, and Cambodia demonstrated that mechanized DSR with low seed rates @ 20–25 kg ha⁻¹ can achieve high yields comparable to transplanting. Precision planting ensures uniform seed distribution, reduces intra specific competition, and enhances tillering capacity. Land leveling and seed treatment further stabilize crop establishment. The results emphasize that mechanization and precision technologies are critical to unlocking the potential of DSR, particularly by enabling the use of high quality hybrids and inbred. However, adoption depends on farmer access to machinery, training, and supportive policies.

5.2 Weed Management in DSR

Weed infestation emerged as the most critical constraint in dry seeded systems, leading to yield losses, herbicide resistance and shifts in weed flora toward difficult to control species such as weedy rice. Integrated Weed Management (IWM) strategies including new herbicide molecules, mechanical tools, precision application and crop traits such as anaerobic germination tolerance were identified as essential interventions. The discussion highlights that weed management in DSR cannot rely solely on chemical control; instead, it requires a holistic approach combining cultural, mechanical and genetic solutions. Without effective weed management, the economic viability of DSR remains limited.

5.3 Evaluation of Deep Water Rice Mutant (LD-200-1-3-3-4) in Gopalganj

The deep water rice mutant line LD-200-1-3-3-4 produced statistically higher grain yield (1.98 t ha⁻¹) under broadcasting at a seed rate @ 22.5 kg ha⁻¹. Its superior performance is attributed to strong culm elongation ability, early vigor and resilience under prolonged submergence. Broadcasting proved to be a practical establishment method in flood prone ecosystems where transplanting is not feasible. Result demonstrates that genetic improvement of deep water rice can significantly enhance productivity in vulnerable ecosystems, ensuring food security in areas prone to seasonal flooding.

5.4 Evaluation of Aus Rice Genotypes in Jhum Ecosystem (Chottogram Hill Tracts)

For hilly areas upland jhum systems, Binadhan-21 consistently outperformed other aus rice genotypes, producing the highest yields under integrated management. Its adaptability to shallow soils, irregular rainfall and high weed pressure makes it particularly suited to hill ecosystems. Integrated management practices including precise seed placement, site-specific nutrient management and improved weed control were critical in stabilizing yields. The discussion emphasizes that genotype × management interactions are key in upland systems and Binadhan-21 represents a promising option for scaling in jhum cultivation.

5.5 Economic Analysis of Tillage Methods (DSR, PTR, UPTR)

Economic evaluation showed that PTR had the lowest expenditure and highest net profit, with a BCR of 1:1.63. UPTR provided moderate profitability (BCR 1:1.48), while DSR recorded the lowest returns (BCR 1:1.32). These results reinforce that profitability is closely tied to yield stability and weed management costs. While PTR remains dominant, UPTR offers a compromise between water saving and profitability. DSR is less profitable at present, holds potential if integrated with improved technologies and adapted cultivars. The discussion highlights that economic viability is the key driver of farmer adoption and DSR must demonstrate competitive profitability to replace transplanting. The experiments illustrate that DSR faces significant agronomic and economic challenges but also offers opportunities for resource conservation, climate resilience and labor savings. Success depends on integrating genotype adaptation (e.g., LD-200-1-3-3-4, Binadhan-21) with

management innovations (precision planting, IWM, SSNM, irrigation scheduling) and tailoring practices to specific agro-ecological zones (broadcasting in deep water areas, dibbling in hilly Aus season, line sowing in drought prone Barind regions). The future of DSR in Bangladesh lies in genotype × management × environment integration, ensuring that the system evolves into a sustainable alternative to conventional transplanting.

6. CONCLUSION

Experiments across drought-prone regions Rajshahi and Chapainawabganj, flood-affected deep water ecosystems Gopalganj and upland jhum systems Chottogram Hill Tracts highlight both the constraints and potential of Direct-Seeded Rice (DSR) as an alternative to conventional puddled transplanting. While PTR remains the most profitable and highest-yielding method under current practices and unpuddled transplanting (UPTR) offers intermediate performance with moderate water savings, DSR generally suffers from lower yields and profitability due to weed pressure, reduced straw yield, and higher management costs. Targeted trials, however, demonstrate that DSR can be strengthened through genotype adaptation and integrated management. The deep water rice mutant line LD-200-1-3-3-4 achieved statistically higher yields under broadcasting in flood-prone Gopalganj, while Binadhan-21 showed superior performance in jhum systems under integrated management. The future of DSR in Bangladesh ensuring that a resource-conserving, climate-resilient and labor-saving technology viable and economically sustainable.

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