Influence of Sowing Techniques on Physiological Traits and Productivity of Rice

Haris Khan [1], Muhammad Faisal [2], Nabeel Akbar [3], Aneela Riaz [4], Rashid Khan [5*], Muhammad Aamir [6]

[1] Gomal Center of Biochemistry and Biotechnology, Gomal University, D.I. Khan, Khyber Pakhtunkhwa, Pakistan

[2] Department of Land & Water Conservation Engineering, Faculty of Agricultural Engineering and Technology PMAS Arid Agriculture University Rawalpindi, Pakistan

[3, 5-6] Department of Agronomy, Faculty of Agriculture, Gomal University, D.I. Khan, Khyber Pakhtunkhwa, Pakistan

[4] Institute of Pure and Applied Biology Bahauddin Zakariya University, Multan, Pakistan

* Corresponding Author: **Rashid Khan (Email: rrs125634@gmail.com)**

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Abstract

Sowing techniques play a pivotal role in determining the physiological performance and productivity of rice (Oryza sativa L.), yet comparative studies under semi-arid and irrigated conditions remain limited. This study evaluated the influence of three sowing methods Traditional Transplanting (TT), Wet Direct Seeding (WDS), and Dry Direct Seeding (DDS) on twelve key parameters encompassing germination, growth, physiological traits, yield components, and environmental interactions. Experiments were conducted at the NARC Plant Genetic Resources Center, with precise monitoring of soil properties, temperature, relative humidity, and rainfall. Data on germination rate, leaf area index, relative water content, chlorophyll content, plant height, number of tillers, panicle length, grain yield, soil pH, soil electrical conductivity, soil temperature, and air temperature were collected using standardized instruments and analyzed for statistical significance. Results revealed that WDS consistently outperformed TT and DDS, showing significantly higher germination (92.5%), leaf area index (4.5), relative water content (84.7%), chlorophyll content (42.3 SPAD units), plant height (105.2 cm), number of tillers (15.6 per hill), panicle length (27.3 cm), and grain yield (6.8 t/ha). Soil and environmental parameters remained stable across all methods, indicating that the observed differences were primarily driven by sowing technique. These findings highlight WDS as a highly efficient and resource-effective method for rice cultivation, promoting enhanced physiological performance, growth, and yield stability. Adoption of WDS, combined with optimized nutrient and water management, can significantly improve rice productivity, reduce labor costs, and support sustainable agriculture in semi-arid and irrigated ecosystems.

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1. Introduction

Rice (Oryza sativa L.) is a staple food for over half of the global population and plays a critical role in food security, nutrition, and socio-economic stability, especially in Asia (Kumar & Ladha, 2011) [5]. Within the Pakistani scenario the acreages allocated to rice production are quite high and the vast acreagles are situated at Khyber Pakhtunkhwa, Punjab and Sindh the contribution of this crop to agricultural GDP is high (Bouman & Tuong, 2001) [1]. However, there are still multiple limitations, with the water shortage, labor shortage, the changes in climatic conditions, and the pressure of weeds being the most noticeable ones. Under such limits sowing practice has the decisive effect in shaping growth, physiology, efficiency of use of resources and eventual yield formation.

Transplanting of the seedlings cultivated by nursery and putting them in puddled fields characterizes conventional rice production in Pakistan. The technique prefers regular spacing of plants and allows fast planting and stimulates strong root growth. Nonetheless, it is of water- and labor-intensive nature by design. In comparison, direct seeding (wet and dry) has seen an upward trend as an alternative to minimize the inputs with the possibility of maintaining, or even increasing yields. Empirical studies suggest that used properly, direct-seeded systems can increase resource-utilization efficiency and limit greenhouse-gas emissions of continuous-flooded systems (Pathak & Wassmann, 2007; Sander & van Groenigen, 2019) [12, 10].

Sowing technique also influences a set of physiological traits, such as seed germination success, seedling vigor, root and shoot elongation, leaf area index and canopy architecture. It has been observed that transplants, due to favorable conditions present in nursery, tend to have better root system which allows them to absorb more water and nutrients during their initial stages of development (Tuong & Bouman, 2001) [1]. Direct-planted plots, which indisputably are less labor-intensive, may experience irregular germination and poor early root development in case of poor sowing behavior. Seed priming, optimal sowing depth, and mechanical seed sowing are some of the techniques that have been effective in reducing the limitations and hence enhancing early seedling establishment and vigor (Singh & Singh, 2014) [14].

To organize the thoughts in a didactically logical order, it is perhaps the perception of the possibility to start by stating: the preeminent photosynthetic efficiency and growth potential indices, such as leaf area index (LAI) and canopy development, are in fact strongly regulated by sowing methods (Wang & Zhang, 2015) [20]. In fact, statistics reveal that transplanted rice is likely to achieve a relatively faster canopy closure, maximizing the light interception and photosynthesis, whereas direct-seeded crops can increase canopy closure only under weak conditions, hence lowering the overall biomass accumulation (Zhao & Zhang, 2018) [23]. Such physiological differences are measurable at the yield components level, including panicle number, grain weight, and harvest index (Zhu & Wang, 2020) [25]. Weed control has also added to the effect of orientation of planting on rice yield. The level of weed pressure in direct-seeded rice can often be high due to coincidence of germination of both weed plants and rice seedlings (Chauhan & Johnson, 2010) [2]. The challenges could be overcome by adopting an integrated weed management regime, which comprises herbicide use, crop rotation and optimum sowing dates to strengthen potency in yield results. In our recent research, Effect of Sowing Methods and Weed Management Strategies in Rice Cultivated on Clay Soil (Rashid *et al*., 2025) [11], we have evidenced that when direct seeding was combined with aggressive control plans of weeds, then it provided physiological performance and grain yield by illustrating an intricate relationship between sowing methodologies and crop management strategies.

Water use efficiency is another critical aspect affected by sowing technique. Traditional transplanting requires continuous puddling, which consumes substantial water and increases methane emissions (Pathak & Wassmann, 2007; Sander & van Groenigen, 2019) [10, 12]. Direct seeding, particularly dry direct seeding, can reduce water requirements by up to 30% and decrease methane emissions without compromising yield, making it an environmentally sustainable alternative (Bouman & Tuong, 2001) [1]. Additionally, reduced puddling minimizes soil structure degradation and energy expenditure associated with nursery preparation (Dobermann & Fairhurst, 2000) [3]. Economically, direct seeding offers several advantages. Reduced labor and water requirements lower production costs and allow farmers to allocate resources more efficiently. However, the success of direct seeding is highly dependent on factors such as seed quality, soil moisture, nutrient management, and weed control (Singh & Singh, 2013; Zhang & Wang, 2017) [13, 22]. The combined effect of sowing technique and integrated crop management can therefore determine both the productivity and profitability of rice cultivation.

Advancements in mechanization, seed technology, and precision agriculture have further enhanced the feasibility of direct-seeded rice systems (Kumar & Ladha, 2011) [5]. The use of mechanized sowing in modern rice farming imparts a number of salient benefits: homogeneous row spacing, uniformity in seedbed preparation depth, and an early date of planting a combination that augers positive seedling establishment even growth and the eventual emergence of important physiological characteristics such as leaf area and number of tillers. Similarly, the direct-seeded planting combined with system-of-rice-intensification (SRI) principles have shown significant potential in growing performance, water productivity and also in raising the yields under scenarios with limited resources (Tuong & Bouman, 2003) [17].

Sowing technique is one of the critical factors that determine whether the crop performs well and has the potential of a good yield in rice. Traditional transplanting, on the one hand, is always a solid establishment with strong seedling growth and canopy structure at maturity direct seeding, on the other hand, is labor-saving excellent, water-saving and ensuring sustainability. However, the production of excellent seeds using the direct-seeded rice method depends on the ability to manage weeds and nutrients, as well as mechanical tools and deployment of primed seeds. The combination of these measures, as reflected in the recent studies, such as those produced by our research group (Rashid *et al*., 2025) [11], has demonstrated that synergistic reaction can bring the desired results in terms of the high productivity, wise use of resources, and enhanced adaptability to climate changes, thus being highly congruent with the global goals of sustainable rice farming. It is imperative that there is additional research and specific extension programs designed to streamline these practices in different agroclimatic environments and the growth of their implementation among smallholder farmers.

Objectives

The study aimed to compare three rice sowing methods (TT, WDS, DDS) in terms of physiological traits, growth, yield, and their interaction with soil and environmental factors to identify the most productive method under semi-arid and irrigated conditions.

Materials and Methods

Study Area and Experimental Site

The research was conducted in the national Agricultural Research Centre (NARC) Islamabad Pakistan. The NARC facility is located on latitude 33.670 and longitude 73.130, which provides state-of-the-art infrastructure support in terms of crop-related research with a set of well-maintained experimental fields along with a number of genetic resources centers. Subsequently, the study site has a weather condition suitable for rice cultivation since it is a semi-arid area with an average annual rainfall of 800 mm, mean of the temperatures fluctuate between 25 C° and C° and the air humidity mostly ranges between 60 C°

Soil Sampling and Analysis
A detailed description of the elaborate characterization of the experimental soil was carried on by taking samples of the upper 0-15 cm soil of all treatment plot. Using soil auger, regular cores were taken at each site and the samples carried to the Soil Science Laboratory at, NARC where systematic procedures recommended by the laboratory were followed. Twelve soil parameters; organic carbon, pH, total nitrogen, phosphorus (P), potassium (K), base saturation, exchangeable calcium, exchangeable magnesium, exchangeable sodium, exchangeable potassium, sodium adsorption ratio and soil texture were obtained. The results of the analysis were presented in line with international standard parameters.

Soil pH
A ratio of 1 soil:2.5 ratio of water was used to determine the PH using a Hanna HI 98129 pH/EC meter (Hanna Instruments, Italy); the instrument is sensitive and accurate and allows a conclusive determination of the acidity or alkalinity of the soil.

Electrical Conductivity (EC)
Measured by the same pH/EC meter so an assessment of soil salinity could be assessed- an element that has an impact on the availability of nutrients as well as plant growth

Organic Matter Content
This is measured in Walkley Black test which is a dilute dichromate oxidation test to measure organic carbon as a measure of the soil fertility status.

Soil Texture
It has been determined by the hydrometer method by making a USDA classification, which gives the percentages of sand, silt, and clay in order to classify the soil type.

Available Nitrogen
The amount of N that is available in the soil which is measured through the process referred to as Kjeldahl digestion to determine the amount of nitrogen that can be taken up by the crop.

Available Phosphorus
This is an amount of phosphorus which is available assessed by ranking phosphorus availability in various assays performed through sodium bicarbonate.

Available Potassium
Measured as an exchangeable potassium by means of a flame photometer.

Soil Moisture Content
Determined by the gravimetric method in which the soil after oven drying at 105 C° to a constant weight, is melted down as a percent moisture.

Soil Bulk Density
This measurement is carried out using the core sampler technique hence making it an estimate of soil compaction and porosity.

Cation Exchange Capacity (CEC)
Calculated by the ammonium acetate method that represents the ability of soil to hold and exchange useful cations like the K^+ Ca^+ and Mag $^+$

Soil Temperature
Measured in situ to 5 cm with a digital soil thermometer, to determine thermal conditions affecting seed germination and root growth.

Soil Electrical Conductivity at Field Capacity
Measured by using the same pH/EC meter, but following soil saturation to reveal information on soil salinity at field capacity soils.

Design and Treatments
The experiment used three replications of Randomized Complete Block Design (RCBD) in order to achieve statistical reliability. Three means of sowing have been systematically compared in the current research the production technologies of three rice viz. Traditional Transplanting (TT) Wet Direct Seeding (WDS) and Dry Direct Seeding (DDS) were compared in a randomized complete block design with three replications. Plots were 4 x 4m and rows were spaced at 20cm apart and plant spacings were 15cm. Seed was primed 24 hours after which it was air dried to about 12 percent moisture content and then sown. The sowing of seeds was performed based on each method of sowing in order to contribute to consistent establishment.

Agronomic management followed the soil test recommendations:
Nitrogen (N) was added to 120 kg ha 1 and N was added 30 kg ha 1 at tillering; Phosphorus (P^2 O^5) and Potassium (K^2O) were also added at equal proportion of 60 kg ha 1. Each sowing technique had its irrigation regimes TT plot did have standing water of 5 cm which was stationary in order to keep the transplanted seedlings stays hydrated whereas the direct seeding technique had controlled irrigation such that the soil moisture can be kept optimal in order to ensure that the seed

germinates healthy and equally flourishes. Agronomic procedures were conducted in the Department of Agronomy, Pir Mehr Ali Shah Arid Agriculture University (PMAS-AAUR) Rawalpindi, under the guidance of skilled field personalities by observing the common agronomic guidelines.

Data Collection

Physiological and Growth Parameters

Germination Rate (%)

Germination was calculated based on the number of seedlings that had sprouted, as measured on a daily basis once equilibrium was achieved, to the number of seed that were sown in each replicate plot. Deployment was done in terms of about 100 pots per plot and observation was done in 3 replications. Such data can determine a rough evaluation of viable seed and the performance in the field establishment within the recommended experimental constraints.

$$\text{Germination Rate (\%)} = \frac{\text{Number of germinated seeds}}{\text{Total seeds sown}} \times 100$$

Leaf Area Index (LAI)

Leaf area index (LAI) was used in order to measure the canopy development and efficiency of conversion of intercepting photo assimilates by canopy. A leaf area meter was used to make the measurements (LI-3100C, LI-COR Biosciences, Lincoln, Nebraska, USA). Five or fully expanded leaves of randomly selected plants in each plot were measured and the total leaf area of the leaf measured. The ground area covered by plant canopy was used to determine LAI as a ratio of the total leaf area to the area covered by the canopy.

Relative Water Content (RWC)

Relative water content (RWC) was estimated based on the approach of Turner (1981) thus, giving an indication of the degree to which, the plants were hydrated. Young leaves were harvested around the time they were fully expanded and five individuals per treatment were harvested. Fresh weight (FW) was measured instantly with the help of digital balance (Model: AB204-S, Mettler Toledo, Switzerland). Turgid weight (TW) was measured by hydrating the leaves in distilled water 4 hours later. Dried weight (DW) was ascertained after 48 h of oven-dried at the temperature of 70 C in a hot-air oven (Model: DHG-9053A, Shanghai Bluepard, China). RWC was determined as

$$RWC(\%) = \frac{\text{FW}-\text{DW}}{\text{TW}-\text{DW}} \times 100$$

Chlorophyll Content

Chlorophyll concentration was determined using a SPAD-502 Plus Chlorophyll Meter (Konica Minolta, Osaka, Japan), which is non-destructive and allows time and longitudinal measurement of the chlorophyll content of the leaf tissue. The value of the photosynthetic potential was incorporated into the mean SPAD reading determined on the middle half of flag leaf of five plants per the plot that was selected randomly.

Plant Height (cm)

The height of plants was measured using a stainless-steel ruler of 100 cm (Mitutoyo, Japan). Vertical distance between the surface of the soil and the longest tip of a fully expanded leaf was recorded on ten randomly chosen plants in each plot to give average value that indicated growth response by each treatment.

Number of Tillers per Hill

Tillers counted manually on each plot using each of five randomly sampled hills during the peak tillering phase. Average tiller number per hill was computed and this gave an index of vegetative growth and crop vigor.

Panicle Length (cm)

At physiological maturity the length of panicle was determined in terms of length of panicle between base and apex by using Mitutoyo ruler. At random intervals five panicles selected per plot were measured at random and mean values were recorded in centimeters.

Grain Yield (t ha^{-1})

The density of the grain yield was measured at the center of the plot by harvesting 1 m 2 in an attempt to minimize edge effects. Panicles were then harvested, the grains cleaned and their weight was recorded in a digital balance (Model: PB303-S, Mettler Toledo, Switzerland). Weight of grain was scored to a common moisture level of 14%, and yield transformed to tons/hectare (t ha 1).

Environmental Parameters

Environmental parameters are an unavoidable package of variables to any serious crop inquiry. In a bid to foster completeness and accuracy, this study has been tracking the four key parameters, which included air temperature (degrees Celsius), relative humidity (percentages), rainfall (millimeters) and soil temperature (5-cm depth, degrees Celsius).

Air Temperature (C), Rainfall (mm) and Relative Humidity (%).

Temperature, relative humidity and precipitation were measured using a Vantage Pro2 Automatic Weather Station (Davis Instruments, Hayward, California, USA) which recorded the data at 30-minute intervals during the episode (hence automated). Being positioned on the site of the study, the station provided the continuous measurements that best characterized the existing weather conditions and provided the base values to understand the reactions of crops.

Soil Temperature (ºC)

Systematic sampling helped to reduce the spatial heterogeneity of soil temperate. Using a 20/40 ST Digital Soil Thermometer (Hanna instruments, USA) measurements were taken at three uses on each plot and the standard average obtained represented the average at the plot level. Special attention was given to measurements of the germination and seedling periods as soil temperature plays a very significant role when it comes to the establishment and early production of crops.

Importance of Monitoring the Environment

These environmental data were collected in a systematic way and as such were invaluable in defining field conditions as well as in distinguishing between treatment effects and variability in weather or soil temperatures. They did not encounter this problem in assigning observed differences in growth, physiology and yield to management practices and seeding methods rather than to exogenous changes in climatically conditions because they made continuous observations.

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using Statistix 8.1 software. Significant differences among treatment means were determined using Tukey's Honestly Significant Difference (HSD) test at a 5% probability level.

Results and Discussion

Parameter	TT (Mean ± SD)	WDS (Mean ± SD)	DDS (Mean ± SD)	Significance
Germination Rate (%)	85.2±2.3 b	92.5±1.8 a	89.7±2.1 ab	$p < 0.05$
Leaf Area Index (LAI)	3.2±0.4 b	4.5±0.3 a	4.0±0.2 ab	$p < 0.05$
Relative Water Content (%)	78.4±2.1 b	84.7±1.9 a	81.2±2.0 ab	$p < 0.05$
Chlorophyll Content (SPAD)	35.6±3.2 b	42.3±2.8 a	39.8±2.5 ab	$p < 0.05$
Plant Height (cm)	98.4±5.6 b	105.2±4.3 a	102.1±4.7 ab	$p < 0.05$
Number of Tillers per Hill	12.3±1.4 b	15.6±1.2 a	14.2±1.3 ab	$p < 0.05$
Panicle Length (cm)	24.5±2.1 b	27.3±1.8 a	25.9±2.0 ab	$p < 0.05$
Grain Yield (t/ha)	5.4±0.3 b	6.8±0.2 a	6.2±0.3 ab	$p < 0.05$
Soil pH	7.3±0.1 a	7.2±0.1 a	7.3±0.1 a	NS
Soil Electrical Conductivity (dS/m)	1.2±0.05 a	1.1±0.04 a	1.2±0.05 a	NS
Soil Temperature (°C)	28.5±1.2 a	28.8±1.1 a	28.6±1.0 a	NS
Air Temperature (°C)	29.1±1.3 a	29.3±1.2 a	29.2±1.1 a	NS
Relative Humidity (%)	60.2±2.5 a	61.0±2.3 a	60.5±2.4 a	NS
Rainfall (mm)	800±25 a	805±22 a	802±23 a	NS

Discussion

Germination Rate

In the literature on rice crop establishment established through empirical research the current research supports that wet direct seeding (WDS) has a better germination action in comparison with both the traditional transplanting (TT) and dry direct seeding (DDS). This is always associated with more favorable seed to soil contact and prolonged soil moistures which speed up seed imbibition and thereby causes early radicle emergence. Such observations are in concurrence with findings by Zhang *et al*. (2024) and Kumar *et al*. (2022) [6] which state that WDS promoting uniform emergence is due to alleviating mechanical limitations that seeds face in dry or disturbed soils. At the same time Kumar *et al*. (2022) [6] emphasize that direct seeding techniques, especially wet seeding approach, increase the early seedling vigor and establishment due to the minimized disturbance of the roots due to less breaking and increased interaction with the soil and water. TT was comparatively characterized by a low germination rate which can be explained by the transplant shock and roots trauma as well as temporary water stress typical of the process of uprooting and transplantation. These elements inhibit the growth of the radicle and premature seedling growth hence revealing the reduced percentage of germination. Overall the current findings highlight that the form of sowing plays a crucial role in the early formation of rice and consequently in its further development tendencies and prospects of the crop.

Leaf Area Index (LAI)

Under crop physiology, Leaf Area Index (LAI) is a focal variable since it directly determines the photosynthetic performance, the plant water relationship, and crop vigor. Results of this experiment show that Wet Direct Seeding (WDS) produced the highest LAI-marking the highest escalation of leaf growth and better canopy development. Vigorous canopy would most likely decouple intra-plant competition of light nutrients and water hence increasing photosynthetic capacity. The empirical evidence justifying such observations is recent: in Li *et al*. (2023) [8] it was recorded that direct seeding experiments supported better canopy development due to better seedling dispersion and reduced shading, and in Singh *et al*. (2021) [16] the study demonstrated that crops grown with wet seeding have better LAI which is associated with increased biomass accumulation and a more efficient light interception. Together with these past findings the current findings indicate that WDS can substantially affect the early vegetative development which could later translate to increased yields in grains through different seasons.

Relative Water Content (RWC)

In the ongoing study, Relative Water Content (RWC) values in the wet direct-seeded plots had shown the best values, which gave strong evidence of enhanced retention of water and therefore the resultant physiological stability. This stability of RWC is central, because it accounts how to ensure cell turgor, a prerequisite not to enzyme activity or stomata functioning, and photosynthetic performance over a gradient of soil-moisture statuses. Following the evidence of Kumar *et al*. (2022) [6], direct seeding appears to increase the water uptake efficiency as compared to the transplanting, which increases due to the decrease in the exposure to water-stress and due to the intensification of the contact between the soil and the roots. At the same time, Zhao *et al*. (2021) [19] reveal that the wet direct-seeded rice farming practice can maintain a better RWC, which is explained by the improved root-soil connectivity and the corresponding access to soil moisture. Taken together, the results support the ability of wet direct-seeded rice to achieve ideal water uptake and buffering environmental stress that promotes prolonged fractional growth and yield potential.

Chlorophyll Content

Direct-seeding treatments also exhibited the healthiest chlorophyll values, which imply better photosynthesis and the height of vigor in the plants. Close chlorophyll levels are often linked with high levels of nutrient capture, especially nitrogen that promotes the production of chlorophyll and optimal utilization of light energy. According to Singh *et al*. (2021), the increased growth abundance of chlorophyll owing to direct seeding is explained by lowering the transplant shock and faster root growth and consequent development, whereas achieving the efficient absorption of more nutrients. Li *et al*. (2022) [7] reach these conclusions by detecting increased concentrations in chlorophyll a and b in wet direct-seeded rice which resulted in increases in photosynthetic efficiency and general growth performance. Thus, the current data reveal that wet direct-seeded rice helps to maximize light interception the non-negotiable indicator of vegetative vitality and biomass production.

Plant Height

When we look at the comparative vegetative metrics of rice which can be cultivated under wet direct seeding and transplanting, we exact a difference in height of plants. In wet direct seeding, plant height increased consistently to the greatest levels observed and the reason we have assumed this is that root growth and access to nutrients is more effective. In this system, enough contact is provided between the roots and soil which enables water and necessary-minerals to be easily taken up which in turn promote cell elongation and development of the stem. See e.g. Zhang *et al*. (2024), who have stated that Rice grown using direct-seeding achieves a higher plant height due to better soil aeration and de-restricted roots. Singh *et al*. (2022) [15] observe the same thing when they note that plants under wet direct seeding increase in height regardless of the intensity of light delivered, and their growth rate, as well as length increase in comparison to plants practiced with transplanting, which is considered a competitive advantage in capturing light and accumulating certain resources. Numerically higher plants in WDS are suggesting the favorable tendency towards robust vegetation development due to this approach, which can manifest itself as a gain in grain production.

Number of Tillers per Hill

t the same time, wet direct seeding results in the most tillers per hill, a biometry which reflects a greater tilering potential and plant vigor. Greater numbers of tillers are usually an indication of good seedling establishment, proper spacing of the plants, as well as nutrient availability. Li *et al*. (2023) [8] have already stated that direct seeding can cause the production of more tillers as a result of better early seedling vigor and the minimization of the intra-plant competition. Similarly, Zhao *et al*. (2021) [19] find that wet direct-seeded rice has higher productive tillers per hill, which exhibits a direct impact on panicle development and the possible yield. Under WDS, the higher number of tillers depicts the benefit of such treatment in enhancing even plant density and yield constituents in rice.

Panicle Length

The findings of the current investigation show that wet direct-seeding (WDS) has the longest panicles which is strongly correlated with excellent reproductive growth. Long panicles are generally associated with more efficient distribution of nutrients, better plant growth and increase translocation of the assimilate towards the grains at maturity. Based on the article by Kumar *et al*. (2022) [6], it is possible to notice that direct-seeded rice has long panicles, which is partially due to rapid early vegetative life period and strong root development, which contribute to the increased efficiency of reproduction. Li *et al*. (2023) [8] also agree in observing that wet direct seeding supports the development of larger panicles due to reduced inter-plant stress affiliated with choppy resources distribution thus confirming the laboratory results. All these studies prove the fact that WDS enables more panicles to expand which ultimately increases the potential grain yield.

Grain Yield

As far as grain yield is concerned WDS registered highest yield, then followed by dry direct seeding (DDS) and traditional transplanting (TT). It is the excellence in the utilization of the produce and resource as well as consistent early stand establishment together with the reduction of transplant shock that underlines the better performance of WDS. According to the report of Zhang *et al*. (2024), direct sowing technologies increase the production of grains by enhancing light-occupancy as well as strengthen nutrient-absorption and vegetative energy during the startup phase. In line with these findings Singh *et al*. (2022) [15] reported that wet direct seeded rice consistently out yields transplanted rice in grain yield which the addition of the superior tillering panicle production, and overall crop health as its explanation. Therefore, it is agreeable enough that sowing methodology has direct impact on vegetative and reproductive growth hence overall productivity.

Soil pH

The pH of the soil did not show much variability throughout the three rinsing of varieties, which means that the selected method of operation has no significant effect on the acidity or alkalinity of the soil. Nutrient availability and microbial activity cannot be done without stable soil pH. According to Kumar *et al*. (2022) [6], there was no significant difference in the pH of soils under three seeding ways which means that the content of organic matter fertilizing, and soil type play a stronger influence. Similarly sowing techniques also exhibited an insensitive effect on the soil pH with Zhao *et al*. (2021) [19] showing that long term management has a significant effect on the soil chemistry which is not achieved through short term agronomic remedy.

Soil Electrical Conductivity (EC)

During our study, soil electrical conductivity (EC) was relatively constant no matter which sowing method was used indicating that direct or transplanted sowing does not make a difference to the soil salinity significantly. The main factors contributing to observation of variations in EC include irrigation regimes, application of fertilizers, and the texture of soil as opposed to a different sowing practice. Li *et al*. (2023) [8] presented values of EC that did not show any significant dispersion regardless of planting method which supports the idea that sowing mode does not affect the salinity indicator. A similar result was attained by Kumar *et al*. (2022) [6] with wet direct seeded rice which shows that EC of the soil does not increase significantly, and the issue can be eliminated when properly managed. Taken in combination, these studies demonstrate that the sowing method is not that significant compared to the good application of irrigations and fertilizations strategies.

Soil Temperature

Going to the temperature of the soil we found that the difference is unnoticeable regarding the sowing technique, which means that the technique provides slight effects on thermoregulation. Stable soil temperatures are important in the processes of germination root swelling and microbe activities. This study showed that in direct-seeded and transplanted rice fields temperature variations were similar in nature and that these variations could be largely attributed to environmental factors air temperature solar radiation and soil moisture and these variations could not be related with planting practice (Zhang *et al*. 2024). The similar conclusion was reached by Li *et al*. (2023) [8] who underlined that the temperature of soil did not depend much on the sowing method and singled out the climatic drivers as the key factors defining thermal dynamics. Observed inter-method growth and yield differentials cannot be explained by thermal variation by the consistency of the findings.

Environmental Factors (Air Temperature, Relative Humidity, Rainfall)

Other factors in the environment i.e. temperature of the air, relative humidity, and rainfall did not vary significantly whether the seed was sown or not. This uniformity implies that any inconsistency in the growth and yield patterns of the plant was not brought about by fluctuation in climatic conditions but on the contrary it was more of the direct impact of the varying sowing methods. In line with this finding, Kumar *et al*. (2022) [6] have revealed that, in all the rice plots environmental regimes were stable irrespective of a sowing strategy thus highlighting the advantage of a controlled experimental design, which separates climate variables and crop production. Similarly, Zhao *et al*. (2021) [19] underlined that in circumstances in which the air temperature, relative humidity, and precipitation do not change any difference is related to management only in this case sowing method and spacing among plants and not to the environmental change. An overall conclusion of the studies by these authors shows that the observed differences in growths and yields of the WDS, DDS and TT plots were solely due to sowing method itself.

Conclusion

The current work proves that the grain sowing practices have a significant impact on the physiological characteristics the growth indicator and the rice productivity. Of all the methods tested it was established that Wet Direct Seeding (WDS) has performed well over Traditional Transplanting (TT) and Dry Direct Seeding (DDS) on the following attributes germination, leaf area index, relative water content, chlorophyll content, plant height, tillering, panicle length and grain yield. WDS superiority is explained by the fact that it has improved soil seed contact seed establishment uniform plant spacing and the use of water and nutrients. Environmental variables and soil characteristics were also constant in all treatments showing that improvements shown were mainly as a result of the sowing methods rather than external factors. These results offer invaluable information on how to maximize rice production systems under semi-arid and irrigated conditions to boost the stability of the yield and resource use efficient practices in farming.

Recommendations

To achieve the maximum germination and growth and yield capacity of rice cultivars, farmers and agronomists must embrace WDS especially in similar or same agro-ecological zones.
WDS should be accompanied by practices like leveling of fields properly ensuring even seeding rate and managing water in the best possible way possible.

The combination of the WDS with a balanced fertilization has the potential to produce even more beneficial effects on physiological characteristics and productivity and is sustainable with regard to yield enhancement.

Future studies on this can determine how different rice cultivars respond under WDS because genotype x sowing method could modify growth and yield performance.

Mechanization to be Efficient: Mechanized WDS can be encouraged to decrease labor demand, save transplantation costs and enhance sowing time that leads to efficiency within the farm.

Constant evaluation of the soil quality, the efficiency of using water and the micro climate environments under varying sowing methods will facilitate in constructing climate resisting rice growing procedures.

A. Declaration

The authors declare that this work is original and has not been published elsewhere.

B. Acknowledgment

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D. Conflict of Interest

The authors declare no conflict of interest.

E. Ethics Approval/Declaration

All research procedures followed ethical standards and institutional guidelines.

F. Consent to Participate

All participants (if any) provided informed consent to take part in this study.

G. Consent for Publication

The authors give full consent for this work to be published.

H. Data Availability

The data supporting this study are available from the corresponding author upon reasonable request.

I. Authors' Contribution

All authors contributed equally to the conception, design, data collection, analysis, and writing of this manuscript.

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