**Enhancing Rice Productivity through Sustainable Water Management Practices**

**Abstract**

One of the largest users of freshwater is rice cultivation, yet conventional continuous flooding techniques are becoming less viable due to climate change and increased water constraints. Innovative irrigation methods like aerobic rice systems (ARS), Saturated soil culture (SSC), intermittent flooding, and alternating wetting and drying (AWD) are being investigated to address this issue. These techniques aid with water conservation without appreciably lowering production. SSC is a cutting-edge irrigation method that creates farming beds divided by furrows with shallow water, mid-season drainage, delayed flooding, sprinkling irrigation, and alternate soaking and drying of fields are further methods to cut down on water use. Similarly, AWD allows the water level to fall below the soil surface in between irrigation events by alternating periods of irrigation and non-flooding. Moreover, it was found that periodic flooding can reduce water use by up to 45%, while AWD can reduce it by 7% to 33%. Intermittent flooding results in 45% water savings, SWP results in 15% less water use than AWD, intermittent irrigation leads to 22%–76% less irrigation water use and 56% less runoff. Moreover, saturation irrigation results in 27% water savings. However, because of institutional, technical, and financial obstacles, many farmers are hesitant to implement them. Wider adoption can be promoted by increasing knowledge, providing financial incentives, and putting supportive policies into place. Long-term food security and the preservation of priceless water resources for future generations depend on adopting these water-saving measures.

**Keywords**: Rice farming, water conservation, sustainable irrigation, AWD, intermittent flooding, climate resilience, food security.

1. **Introduction**

About 70% of the water resources in the world are used by agriculture, making it the biggest user of freshwater (World Bank, 2022). The world's population is predicted to grow dramatically, and by 2050, the demand for food production is forecast to rise by almost 70%. In order to support agricultural productivity, this condition emphasizes the urgent need for more effective water management techniques. Effective water management practices are crucial for maximizing crop productivity and minimizing water wastage. By implementing efficient irrigation systems and water-saving techniques, farmers can enhance crop yields while conserving precious freshwater resources (Ray & Majumder, 2024; Biswas et al., 2025). According to Joshi et al. (2018), rice is a staple food for over 60% of the world's population. Given the increase in the human population over the last ten years, the Food and Agriculture Organization (FAO) has reported that a 70% increase in rice production is urgently needed to fulfil the projected demand by 2050 (FAO, 2018). It is imperative to look at rice agriculture in light of this growing need.

Rice is the staple food for billions of people in the world. However, water shortage is a major threat to sustainable rice production worldwide. It is of utmost importance to explore alternate ways of rice production by using less water for food security (Datta et al., 2017). Rice farming is primarily categorized into four ecosystems: irrigated (which accounts for 50% of total rice production), rainfed lowland (34%), rainfed upland (9%), and flood-prone areas (7%) (IRRI, 2014). The irrigated rice ecosystem is the most productive and plays a vital role in satisfying global food needs. However, its productivity is heavily influenced by factors such as water availability, irrigation methods, water quality, and the duration of standing water in the fields during the growing season (Joshi et al., 2018). Rice might face a threat due to water shortage, and hence, there is a need to follow water-saving strategies in rice cultivation so that production and productivity levels are elevated despite the looming water crisis (Nayaka et al., 2021). On the other hand, the rainfed ecosystem presents a significant opportunity for yield enhancement, as it encompasses 43% of rice cultivation but still has considerable untapped potential. The primary challenges to rice production in this ecosystem include inconsistent water supply—often due to severe droughts or flooding—and poor soil fertility, which can be attributed to its acidic or saline characteristics (He et al., 2020). These adverse conditions complicate efforts in rice genetic improvement programs, thereby increasing the pressure on the irrigated ecosystem.

Recent changes in the environment have brought about a number of abiotic stresses that have a major effect on rice production in all habitats by impeding the growth and development of plants (Joshi et al., 2020). According to Caine et al. (2019), it takes between 2000 and 5000 litres of water to produce 1 kilogram of rice. Further limiting the amount of water available for rice farming is the growing competition for freshwater resources brought on by fast industrialization and urbanization. The need for "more rice with less water" has therefore become essential to guaranteeing food security worldwide (Maneepitak et al., 2019). In all ecosystems, rice farming depends on the availability of water, which makes it necessary to create creative water management strategies that can improve output in various settings. (Carracelas & colleagues., 2019). Either growing rice types that can withstand water stress and flourish with little water or enhancing soil conditions to assist rice growth in water-scarce environments are two ways to effectively manage water.

Saturated soil culture (SSC), which creates farming beds divided by furrows with shallow water, mid-season drainage, delayed flooding, sprinkling irrigation, and alternate soaking and drying of fields, is another method to cut down on water use (Maneepitak et al., 2019). These methods have led to the introduction of promising rice varieties that can be grown in a variety of rice ecosystems by the Indian Council of Agricultural Research-National Rice Research Institute (ICAR-NRRI). These developments are intended to improve water efficiency while also supporting sustainable farming methods that can assist in fulfilling the world's expanding food needs while preserving essential water supplies. In order to ensure that rice continues to be a dependable food source for the world's population, rice producers may adjust to the problems presented by climate change and water scarcity by putting these strategies into practice. In the upcoming decades, attaining food security and sustainable development objectives will depend heavily on the incorporation of cutting-edge agricultural techniques and research into rice production practices (Singh et al., 2021).

1. **Cultivating Resilience: Current Rice Varieties for Water-Scarce Environments**

An issue that is getting more urgent is the supply of water for irrigation, which makes it more difficult to produce rice and other crops at their best yields. As climate change exacerbates water scarcity, scientists and agronomists are looking for new ways to mitigate drought's effects and boost crop yields (Singh et al., 2021). Choosing rice cultivars that are especially suited to the local area is an important part of this endeavour since different types of rice have varied ways of dealing with water scarcity. Yang et al., (2019) conducted a field investigation in which they examined two rice genotypes, Yangliangyou 6 (YLY6) and Hanyou 113 (HY113), in both drought and flooding scenarios. According to the results, physiological characteristics, yield, and grain were all considerably impacted by drought stress throughout the reproductive phase. This emphasizes the significance of selecting drought-tolerant cultivars to maintain output in water-constrained environments. The development of drought-tolerant, high-yielding rice varieties has advanced significantly, thanks to the International Rice Research Institute (IRRI). BRRI dhan from Bangladesh, Inpago LIPI Go 1/2 from Indonesia, M’ZIVA from Mozambique, UPIA3 from Nigeria, Sahod Ulan and Katihan from the Philippines, Hardinath and Sookha Dhan from Nepal, and Sahbhagi Dhan from India are among the 17 types that IRRI has published thus far (Kumar et al., 2014). Because these cultivars are engineered to flourish in harsh environments, they help provide food security in areas that are vulnerable to drought.

With a yield of about 4 tons per hectare under optimal conditions and 1 to 2 tons per hectare during severe drought, the drought-tolerant variety Sahbhagi Dhan has demonstrated impressive performance in India. It is a financially viable option for rice cultivation in regions with limited water resources due to its early maturity, usually within 105 days, and low irrigation requirements, which enable farmers to save up to USD 60 every crop cycle (Basu et al., 2017). For smallholder farmers, who frequently encounter financial difficulties, this economic advantage is especially significant. Similarly, the drought-resistant cultivar Sookha Dhan 2 has shown greater yields at elevations ranging from 1,000 to 1,600 meters above sea level in Nepal, demonstrating its versatility in a range of growing environments (Dhakal et al., 2020). Food security in hilly areas, where water availability might be particularly limited, depends on this flexibility. A drought-tolerant rice cultivar, DRR-Dhan 45, has also been created and released by the Indian Council of Agricultural Research-National Rice Research Institute (ICAR-NRRI). The average production of this variety is 6 tons per hectare, and it also exhibits moderate resistance to key diseases and pests such as rice tungro viruses, sheath rot, and blast (Nirmala et al., 2016). In the face of growing biotic and abiotic stressors, the development of such resilient cultivars is crucial to sustaining rice production. For the purpose of improving agricultural resilience in water-scarce regions, it is imperative that drought-tolerant rice varieties be continuously developed and used. Farmers can reduce the financial risks connected to water scarcity and increase yields by choosing appropriate crops. The importance of developing and promoting robust rice varieties cannot be emphasized enough, especially as climate change continues to threaten global food security.

1. **Boosting Water Efficiency and Productivity in Rice Farming**

Meeting the demands for food and water will become more difficult as the world's population continues to rise. Global food security depends on the sustainable use of agricultural water resources (Kang et al., 2015). Three main strategies can be used to address food shortages associated with water scarcity: (i) increasing water availability by recycling wastewater; (ii) improving water productivity by increasing crop yields or optimizing water usage, or both; and (iii) addressing regional water shortages by importing food, which virtually transfers water (Orgaz et al., 2011). These tactics' main objectives are to optimize the use of available rainfall, utilize scarce irrigation supplies as effectively as possible, and improve crop water use efficiency through integrated practices. Enhancing agricultural water efficiency is a key tactic for India to meet the growing demand for food. Through integrated methodologies, these three initiatives aim to increase agricultural water usage efficiency, make better use of the limited irrigation water, and maximize the use of available rainfall. To meet the growing demand for food, India must improve agricultural water efficiency. This can be achieved through a number of methods and technologies, including (i) improving and streamlining drainage and irrigation systems, (ii) creating and lining field channels and waterways, (iii) leveling and forming land, (iv) installing field drains, (v) utilizing surface and groundwater in complementary ways,(vi) putting into practice and overseeing appropriate cropping patterns; (vii) establishing and enforcing warabandi, or rotating water distribution systems; (viii) creating plans to supply necessary inputs such as credit, seeds, fertilizer, and pesticides; and (ix) improving current extension, training, and demonstration programs on farmers' fields to conserve freshwater and increase irrigation efficiency (Mallareddy et al., 2023).

* 1. **Innovative Irrigation Strategies for Water Conservation**

Particularly in the main rice-growing regions, India's freshwater supplies are coming under more and more strain. By increasing agricultural water productivity—that is, producing more yield or income per drop of water used—freshwater demand can be reduced. Rice is traditionally grown in fields that are constantly flooded, a practice that uses a lot of water and has negative environmental effects even though it increases yield. According to Ishfaq et al. (2020), these include the buildup of dangerous materials like arsenic and mercury, increased methane emissions, and soil degradation. Therefore, it is critical that agricultural research and development concentrate on lowering the water requirements for rice growing and investigating substitutes for the traditional flooding system. India's freshwater supplies are under increasing strain, especially in key rice-growing regions. Improving agricultural water efficiency—that is, increasing output or revenue from each drop of water—is essential to alleviating this strain. Rice farming has historically depended on fields that are constantly flooded, which can be environmentally harmful and use a lot of water even while it increases output (Kumar et al., 2021). This approach may result in increased methane emissions, soil deterioration, and the accumulation of dangerous elements like arsenic and mercury. According to Nelson et al. (2015), agricultural research and development should thus concentrate on identifying methods to lower water consumption in rice growing and investigating substitutes for the traditional flooding technique. Farmers have been given access to a number of cutting-edge methods that have been tested to increase rice production while conserving water. Direct seeded rice (DSR), drip-irrigated DSR, saturated soil culture (SSC), the aerobic rice system, the system of rice intensification (SRI), and alternate wetting and drying (AWD) are some of these techniques. For example, the raised-bed system uses less water and enhances soil aeration by growing rice on raised beds that drain well and are not continuously inundated (Ishfaq et al., 2020). The ground cover rice production technique, which uses shallow water levels with AWD to preserve water, is a further strategy.

Additionally, non-flooded mulching and rice transplanting on non-puddled soil can assist in saving water while preserving high crop yields. To further reduce water use in rice farming, methods such as semi-dry cultivation and intermittent dry spells incorporate intentional periods of drought to enhance plant water efficiency (Kumar et al., 2021). These substitute techniques have a reputation for using less water, improving soil health, reducing greenhouse gas emissions, and lessening the accumulation of toxic compounds in rice grains. Using these methods could be essential to solving India's agricultural water shortage problems.

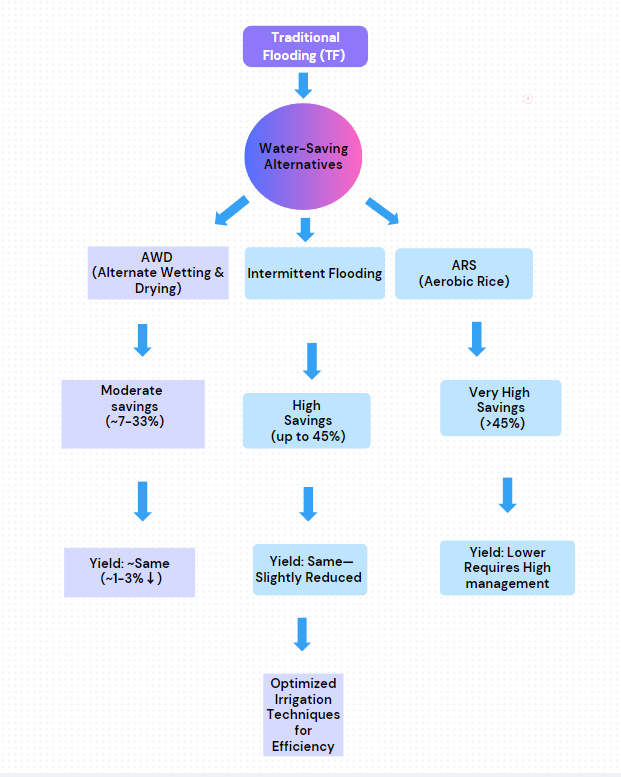
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**Fig 1**: Alternate wetting drying implementation approaches

* 1. **Smart Surface Irrigation Solutions for Enhanced Rice Production**

Despite their low efficiency and homogeneity, which are mostly caused by poor design and water management in alternative irrigation techniques, surface irrigation techniques remain the most widely used around the globe (Masseroni et al., 2017). These techniques, which include furrow, border, and basin irrigation, are frequently characterized by inefficiencies that lead to waterlogging, water waste, salinization, and contamination of surface and groundwater resources (Adamala et al., 2014). Promoting sustainable rice production in gravity-fed irrigation systems, several studies have focused on improving furrow irrigation as well as water-saving techniques. The usage of furrow irrigation for rice production has been growing recently, according to Hardke and Chlapecka (2021), going from less than 1% in 2015 to 10% in 2019. When compared to conventional flood irrigation techniques, crop rotations are easier to implement and require less time and money. For rice farming, furrow irrigation works better than traditional flood irrigation because it uses less water and labor and lowers the amount of arsenic in the harvested rice grain (Stevens et al., 2018). In contrast to rice grown with flood irrigation, some studies have demonstrated that although rice grown with furrow irrigation may yield less, it frequently contains greater levels of arsenic (Aide, 2018). In summary, even though surface irrigation techniques are commonly employed, there is growing recognition of the need for better approaches, especially in furrow irrigation, to maximize water efficiency and reduce hazardous pollutants in rice cultivation.

**Fig 2**: Water-saving alternatives

* 1. **Drip Irrigation Techniques for Enhanced Rice Cultivation**

Although it is a feasible option, drip irrigation is rarely used in rice production systems, and few studies have examined its potential advantages for rice crops. However, Meher et al., (2020) contend that drip irrigation is a terrific way to increase productivity while using less water, which can result in higher yields. When compared to conventional methods, this approach not only lowers irrigation expenses but also contributes to a reduction in overall water use to environmentally sustainable levels. According to Parthasarathi et al. (2018), drip irrigation can boost aerobic rice yields by 29% and increase water-saving effectiveness by 50%, increasing water productivity overall. Furthermore, it promotes improved root health, boosts photosynthesis in the canopy, and enhances the plants' dispersion of dry matter. Drip irrigation systems can result in significant water and energy savings, improve nitrogen use efficiency, and increase net income, according to research aimed at easing the strain on groundwater resources, particularly as aquifers continue to exhaust due to climate change (Sidhu et al., 2019). In a similar vein, Rao et al. (2017) showed that drip irrigation is superior to conventional continuous flooding techniques for rice production, especially when it comes to increasing water productivity and preserving energy.

In conclusion, research shows that drip irrigation has the potential to greatly boost crop yields and improve water efficiency, even if it is not currently commonly used in rice production.

* 1. **Elevating Rice Production with Advanced Sprinkler Irrigation Systems**

Research conducted in the USA on rice production using centre pivot irrigation has shown that sprinkler irrigation can be a practical alternative to traditional flooding methods. This approach not only improves water use efficiency but also helps manage soil water tension (Parfitt et al., 2017). The findings indicate that rice grown with sprinkler irrigation tends to have higher grain yields, better fertilizer use efficiency (FUE), and greater water use efficiency (WUE) compared to rice cultivated in flood-irrigated lowland areas. Moreover, using sprinkler irrigation significantly lowers the levels of arsenic found in the harvested rice grain when compared to flood irrigation (Stevens et al., 2017). According to this, rice production methods that have shifted from traditional flooding to spray irrigation can save water and lessen the buildup of dangerous elements like arsenic and cadmium in the rice grain (Alvarenga et al., 2022; Spanu et al., 2021). This change enables the production of safe rice on soils that could otherwise produce contaminated crops that are inedible.

1. **Water-Saving Irrigation Practices for Rice Production**

Traditional surface irrigation techniques, especially continuous flooding, still dominate rice agriculture for a number of reasons, despite the encouraging findings from studies on micro-irrigation systems like drip and sprinkler irrigation (Islam et al., 2020; Hamoud et al., 2019). First off, surface irrigation has been around for a while, and because of psychological and cultural reasons, many farmers are hesitant to stop using it (Arouna et al., 2023). Second, rice farmers, particularly smallholders, who might not have the means, expertise, or understanding to install micro-irrigation systems—which can be costly and complicated—can more easily use surface irrigation systems. Finally, research indicates that rice yields are frequently lower under micro-irrigation systems than they are under conventional surface irrigation (Mubangizi et al., 2023). In light of this, it is imperative to create and implement irrigation techniques that improve water use efficiency without sacrificing yields. Water-saving techniques have financial benefits as well as environmental ones, such as enhancing fertilizer use efficiency and raising agricultural productivity while lowering energy costs. They also help the environment by conserving water resources and lowering greenhouse gas emissions (Alauddin et al., 2020; Wang et al., 2020). Several water-saving devices have been found through research to help produce rice sustainably instead of continuously flooding. Alternate wetting and drying (AWD), soil water potential (SWP), aerobic rice systems (ARS), effective irrigation regimes (EIR), saturated soil culture (SSC), field water level (FWL), intermittent drainage (ID), leaching and flushing methods (LFM), conventional flooding with midseason drainage (FDF), and non-flooded mulching cultivation are some of these technologies (Ishfaq et al., 2020) AWD has become well-known among them as a water-saving technique for growing rice. AWD allows the water level to fall below the soil surface in between irrigation events by alternating periods of irrigation and non-flooding (Islam et al., 2020). Compared to conventional flooding, this technique can save 7% to 33% of irrigation water without appreciably reducing yields. AWD is, therefore, extensively marketed as a water-saving technique for rice farming worldwide. Even though alternate wetting and drying (AWD) is frequently cited as a top water-saving technology because of its advantages for the economy and the environment, its uptake is still quite low. A lack of institutional support and the intricate interactions between socioeconomic conditions and agricultural practices are the reasons for this hesitancy (Mubangizi et al., 2023; Alauddin et al., 2020). According to research by Hiya et al. (2020) and Massey et al. (2022), intermittent flooding can also improve water use efficiency in rice production as long as a suitable water depth is maintained. For example, Afifah et al. (2015) discovered that, while still attaining notable gains in water use efficiency, flooding a field 1 cm deep saved 45% of the water compared to flooding 5 cm. It is interesting to note that rice yields were comparable under floods at 5 cm and at depths of 1 to 3 cm, and they were higher than those under AWD.

According to Islam et al. (2020), employing soil water potential (SWP) reduced seasonal water use in the Philippines by 15% as compared to AWD. Furthermore, intermittent irrigation increased water usage efficiency by reducing irrigation water use by 22–76% and runoff by 56%, according to a study conducted in Brazil by de Avila et al. (2007–2010). Other research has looked into alternatives to AWD; for example, Albaji et al. (2011) showed that limited irrigation produced a water use efficiency of 13.3 to 13.9 kg/mm, while typical flooding obtained 12.48 kg/mm. Experiments in India showed that although saving 27% of water, saturation yields were on par with flood irrigation. Additionally, studies conducted in Jiangsu, China, showed that shallow water irrigation produced higher yields despite consuming more water (Zhang et al., 2018).

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| Irrigation Method | Water Savings | Yield Impact | Study Reference |
| Alternate Wetting and Drying (AWD) | 7%–33% water savings | No significant reduction in yield | Islam et al. (2020) |
| Intermittent Flooding (1 cm vs. 5 cm depth) | 45% water savings (1 cm depth) | Comparable yield at 1–3 cm depth, higher than AWD | Afifah et al. (2015) |
| Soil Water Potential (SWP) | 15% less water use than AWD | Not specified | Islam et al. (2020) |
| Intermittent Irrigation | 22%–76% less irrigation water use, 56% less runoff | Increased water use efficiency | de Avila et al. (2007–2010) |
| Limited Irrigation | Higher water use efficiency (13.3–13.9 kg/mm vs. 12.48 kg/mm in typical flooding) | Not specified | Albaji et al. (2011) |
| Saturation Irrigation | 27% water savings | Yield comparable to flood irrigation | Experiments in India |
| Shallow Water Irrigation | More water use | Higher yield | Zhang et al. (2018), Jiangsu, China |

**Table 1:** Techniques for Water-Saving in Rice Cultivation

1. **Water-Saving Agronomic Practices for Rice Production**

To increase water conservation in irrigated rice farming, numerous studies have investigated effective agronomic practices (GAP). These methods include the use of rice cultivars that can withstand drought, mulching with plastic and straw, adding organic matter, and applying low tillage techniques. In order to increase agricultural yields and improve water efficiency, each of these techniques is essential. According to Zhang et al. (2021), for example, using rice cultivars that are resistant to drought not only helps sustain harvests during dry spells but also lowers greenhouse gas emissions from rice fields. Given that the availability of water is becoming less predictable due to climate change, this is particularly crucial. Another useful method for regulating soil temperature, weed control, and moisture retention is plastic mulching. Farooq et al. (2019) claim that this technique produces a barrier that reduces evaporation, enabling crops to utilize water more effectively. This is essential for optimizing productivity in regions with scarce water supplies. Straw mulching has also been demonstrated to boost crop yields and enhance soil fertility. Returning straw to the fields can result in notable production gains (averaging 7.9% and 7.5% in various years), according to research by Wei et al. (2019). It can also improve irrigation water use efficiency (IWUE) by 6.3% and 8.3% in 2015 and 2016, respectively. By adding organic matter to the soil and assisting in moisture retention, this technique improves the growing conditions for rice.

Soil fertility and health are further enhanced by the addition of organic materials, such as compost or biochar. The significance of soil amendments in sustainable agricultural techniques was highlighted by Chen et al. (2021), who showed how adding biochar can improve rice growth and yield under water-saving irrigation circumstances. In addition to improving soil structure and supplying vital nutrients, these organic components can help retain water and promote root growth. Water consumption efficiency can also be greatly impacted by controlling crop spacing, planting dates, and seeding rates. Farooq et al. (2019) highlighted that improving these elements, in addition to managing soil fertility and controlling weeds, can result in improved crop water use. This all-encompassing strategy guarantees that plants are more capable of surviving drought and utilizing the water resources that are available. For efficient water management, the crop canopy's structure is also essential. In addition to providing shade for the soil, a dense canopy can absorb sunlight, which is necessary for photosynthesis. By lowering soil temperatures, this shade minimizes crop water loss and evaporation. A well-developed canopy can significantly improve water conservation in rice fields, according to Farooq et al. (2019). Furthermore, a promising technique to lower irrigation water requirements is the System of Rice Intensification (SRI). Wider plant spacing and careful nutrition and water management are two SRI methods that can reduce irrigation needs while preserving or even raising rice yields (Stoop et al., 2009). This method encourages healthier plants and improved soil conditions in addition to conserving water.

In conclusion, increasing water efficiency in irrigated rice cultivation requires a combination of creative water-saving methods and diverse sound agronomic approaches. By using these techniques, farmers may increase crop yields and support sustainable farming systems that can withstand the effects of water scarcity and climate change.

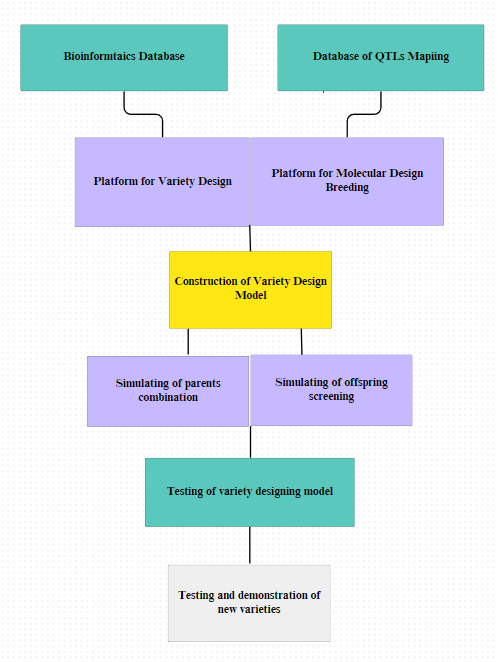
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| Agronomic Practice | Key Benefits | Study Reference |
| Drought-resistant rice cultivars | Sustains yields during dry spells, reduces greenhouse gas emissions from rice fields | Zhang et al. (2021) |
| Plastic mulching | Reduces evaporation, regulates soil temperature, controls weeds, improves water use efficiency | Farooq et al. (2019) |
| Straw mulching | Enhances soil fertility, improves irrigation water use efficiency (IWUE) by 6.3%–8.3%, increases yields by 7.5%–7.9% | Wei et al. (2019) |
| Organic matter addition (e.g., compost, biochar) | Improves soil structure, retains moisture, enhances nutrient supply, promotes root growth | Chen et al. (2021) |
| Optimizing crop spacing, planting dates, and seeding rates | Enhances crop water use efficiency, improves drought resistance, optimizes available water use | Zhang et al. (2021) |
| Developing dense crop canopy | Reduces soil temperature, minimizes evaporation, improves photosynthesis efficiency | Farooq et al. (2019) |
| System of Rice Intensification (SRI) | Reduces irrigation water needs, maintains or increases rice yields, improves plant and soil health | Stoop et al. (2009) |

**Table 2**: Agronomic Practices for Water Conservation in Rice Farming

1. **Molecular Breeding for Rice Improvement**

One of the biggest challenges facing modern agriculture is ensuring global food security in the face of climate change and growing water scarcity. The creation of crop types that can withstand drought is one viable approach to solving this problem. A variety of physiological, biochemical, and molecular alterations in plants contribute to the complex trait of drought tolerance (Joshi and Karan, 2014). Changes in photosynthesis, osmotic adjustment, guard cell regulation, and root architecture are important factors. For example, in order to preserve water during drought, plants may block their stomata, which can limit the uptake of carbon dioxide and lower photosynthetic efficiency (Flexas et al., 2006). Furthermore, by accumulating solutes like proline and sugars, which anchor cellular structures and support metabolic processes, osmotic adjustment enables plants to sustain turgor pressure (Kramer and Boyer, 1995). Since deeper roots can greatly increase drought tolerance, it is also essential to develop root systems to access deeper soil moisture (Lynch, 2013). Additionally, amid water shortages, plants are shielded from cellular damage by the production of certain proteins and antioxidants, which reduce oxidative stress (Foyer and Noctor, 2005).

Breeders are using a number of techniques to increase drought tolerance, such as marker-assisted breeding (MAB), which finds and incorporates Quantitative Trait Loci (QTLs) linked to drought-related phenotypes (Collard and Mackill, 2008). Finding QTLs associated with characteristics like root depth and leaf water potential—which boost grain yield in water-limiting situations—has advanced significantly (Kumar et al., 2014; Pascual et al., 2016). Biparental or multiparent populations have been the subject of a large portion of previous research, which may have limited the genetic variety available for breeding (Bhat et al., 2016). In order to get over this restriction, it is imperative to investigate a wider variety of genetic resources, such as landraces and wild relatives, in order to find new alleles that provide drought resilience. We can better understand the genetic basis of drought tolerance and uncover new QTLs with the help of advanced genomic tools like next-generation sequencing and genome-wide association studies (GWAS) (Huang et al., 2015). Researchers can create more robust crop types that are better able to handle the difficulties presented by climate change and water scarcity by utilizing these technologies and broadening the genetic pool. This would ultimately improve global food security.

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**Fig 3**: Molecular Breeding for Rice Improvement

1. **Future Opportunities: Unlocking New Avenues for Development**

Increasing production in a sustainable way to satisfy growing demand is currently the biggest problem facing rice farmers. Creating high-yielding rice cultivars that are tolerant of severe abiotic stresses and resistant to pests and diseases is essential to achieving this. Such developments can be supported in irrigated areas, but upland and rainfed regions are constrained, particularly in situations where water is scarce. According to research, farmers in drought-prone regions are frequently prepared to pay more for new stress-tolerant cultivars and are willing to accept a decrease in production variability if available (Arora et al., 2019). Two main areas must be prioritized in order to effectively address these issues: improving rice varieties to increase yields in challenging environments and developing crop management systems. Rice farming is made more difficult by climate change, which causes erratic rainfall patterns, more frequent flash floods, and intermittent droughts that are bad for soil health. Changes in soil structure, elevated salinity, and a reduction in genetic diversity are examples of secondary problems that might arise from these climate variations (Arora et al., 2019). Scientists are attempting to use the genetic resources already in place to counteract these impacts. Numerous rice species have a large number of germplasm accessions that have been conserved ex situ, and work is being done to increase the number. Improvement techniques that rely on quantitative trait locus (QTL) mapping obtained from pre-breeding experiments include genomic selection, backcrossing, pyramiding, recurrent selection, and marker-assisted selection (Singh et al.,2021). The selection of cultivars that can be incorporated into breeding programs depends on these pre-breeding techniques.

Transgenic techniques are also being used to improve quality attributes, validate gene functions, and create cultivars that are tolerant and resistant to a range of stressors. In the end, developing rice cultivars with higher water-use efficiency will support environmental sustainability and the Sustainable Development Goals in addition to offering substantial economic benefits.

1. **Enhancing Rice Breeding for Improved Germination Under Water-Limited Conditions**

In Asia, where it is traditionally grown in flood-prone areas, rice (Oryza sativa) is a staple food for almost half of the world's population. However, the creation of rice cultivars that can thrive in water-limited environments is required due to the growing problems brought on by climate change, such as water scarcity and unpredictable rainfall patterns (Heredia et al., 2022). Conventional methods of growing rice frequently depend on ongoing flooding, which uses a lot of water and produces greenhouse gas emissions (Hussain et al., 2015). Therefore, it is imperative to investigate alternate breeding techniques and farming practices that improve water use efficiency.

Recent advancements in breeding strategies have focused on enhancing traits such as anaerobic germination tolerance, which allows rice seeds to germinate in low-oxygen environments often encountered in poorly drained soils (Septiningsih et al., 2013). This trait is particularly important for direct-seeded rice (DSR) systems, where seeds are sown directly into dry or puddled soil, and water availability can fluctuate significantly (Singh et al., 2017). Marker-assisted selection (MAS) has facilitated the identification of quantitative trait loci (QTL) associated with anaerobic germination, enabling breeders to incorporate this trait into elite rice varieties (Ghosal et al., 2019). For instance, the identification of QTLs linked to anaerobic germination has led to the development of rice lines that exhibit improved germination rates under submerged conditions, thereby enhancing establishment success in water-limited environments.

Establishing rice plants in water-limited conditions requires not only anaerobic germination but also early seedling vigour. Varieties demonstrating quick and uniform emergence can outcompete weeds and utilize available nutrients more effectively, which is critical for reaching optimal yields (Mahender et al., 2015). Breeding efforts have stressed the necessity of selecting for early vigour traits, as these can considerably influence the overall performance of rice under dry conditions. Furthermore, root plasticity is another critical trait that allows rice plants to adapt their root architecture in response to varying soil moisture levels (Uga et al., 2013). Varieties with deeper and broader root systems can obtain water and nutrients more efficiently, hence boosting their resilience to drought stress.

The integration of genomic tools and high-throughput phenotyping techniques has further revolutionized rice breeding for water-efficient germination. Genomic selection allows for the rapid identification of favourable alleles associated with water-saving traits, enabling breeders to develop improved varieties more efficiently (Cobb et al., 2019). High-throughput phenotyping methods, such as UAV-based imaging and soil moisture sensors, provide real-time data on plant growth and water stress, facilitating the selection of traits that enhance germination and establishment under limited water conditions (Devia et al., 2019). These technological advancements not only accelerate the breeding process but also enhance the precision of trait selection, leading to the development of rice varieties that are better adapted to water-limited environments.

In conclusion, the need for rice varieties that can germinate efficiently with less water is becoming increasingly critical in the face of climate change and water scarcity. Researchers can create rice varieties that are more suited to water-limited conditions by concentrating on characteristics such as anaerobic germination resistance, early seedling vigour, and root flexibility and by utilizing contemporary breeding procedures. In order to guarantee future food security and sustainable rice production, it will be crucial to keep funding breeding initiatives and using cutting-edge technologies.

**Conclusion**

It is more crucial than ever to make rice production more sustainable as concerns about water scarcity grow. Even though traditional flooding techniques are good at preserving high yields, they waste a lot of water and exacerbate environmental problems like soil erosion and greenhouse gas emissions. In order to address this, scientists have created cutting-edge irrigation methods like saturated soil culture (SSC), aerobic rice systems (ARS), intermittent flooding, and alternate wetting and drying (AWD). These techniques maintain consistent rice harvests while saving a substantial quantity of water. For instance, periodic flooding can reduce water use by up to 45%, while AWD can reduce it by 7% to 33%. Farmers can gain from employing drought-tolerant rice cultivars, improved soil management, and conservation practices in addition to these irrigation advancements to make rice production more water-efficient.

Many farmers, particularly smallholders, are reluctant to implement these water-saving techniques despite their obvious benefits. They find it challenging to move away from conventional irrigation techniques due to a lack of government backing, financial constraints, and a lack of technical expertise. It is necessary to try to educate farmers about the advantages of these new methods because many of them continue to use what they are familiar with. Change can be aided by offering monetary rewards, improved access to irrigation equipment, and legislative backing. Furthermore, water use can be further optimized using precision farming and smart irrigation technologies. To secure rice farming's future, a mix of better irrigation techniques, drought-resistant rice cultivars, and more robust regulations will be essential. By adopting these improvements, we can increase the efficiency of rice production, guarantee food security, and save valuable water resources for future generations.

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Details of the AI usage are given below:

1.

2.

3.

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