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Recent Advances in Sustainable Rice Production: Improving Water, Nutrient and Resource-Use Efficiency

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Rice is the primary food for over half of the world's population, and serves as the basis for transforming the food and nutrition security in Asia, Africa and Latin America. On the demand side, the population of the world is getting closer to 9.7 billion, and the demand for rice will continuously increase despite the increasing strain on the resource base to meet such production needs. The water-requirements of rice cultivation are high and occupy a unique position in the use of global freshwater withdrawn for agriculture, while traditional puddled-transplanted agriculture relies heavily on reliable irrigation and well-trained irrigation labour at crucial transplanting stages. These are increasingly becoming scarce and expensive in most rice producing areas.

At the same time, rice paddies are a large area of anthropogenic CH_4 emitters and, under some irrigation conditions, N_2O, making the crop a focal point for climate change discussions on agriculture. Rainfed and coastal rice systems are vulnerable to yield instability due to erratic rainfall and repeated drought, heat stress at reproductive stages, flash flooding and the secondary soil salinization enhanced by these events. The high costs of fertilisers, fuel and labour are taking a toll on profits, and as many traditional rice belts are seeing an aging farming population and the movement of rural residents to urban areas, timely transplanting of crops is becoming increasingly difficult.

It is evident that these synergic forces are driving a need for transformation beyond incremental changes in the traditional production paradigm. Rice farming needs sustainable intensification – increase in productivity per unit area, water, nutrients and labour with a simultaneous decrease in environmental footprint. It requires a holistic reassessment of crop establishment technologies, water and nutrient management, digital and precision technologies and new technologies for climate-adaptive agronomy. This article aims to document all these overlapping lines of enquiry by summarizing current knowledge on agronomic performance, trade-offs and applicability of the various domains and to suggest a logical research trajectory towards more resource-efficient and climate-resilient rice production systems.

Sustainable Rice Establishment

The traditional method of establishing rice is transplanting, widely practiced in South and Southeast Asia, known as puddled transplanted rice (TPR). Applying a puddle will help the crop retain moisture and prevent early weed flushes and manual transplanting of a nursery-grown seedling enables efficient control over crop stocking rate and early crop uniformity. This is a water-intensive and labour intensive system though; a significant proportion of water usage is needed for land preparation and the window for planting at time is increasingly becoming a constraint due to the chronic shortage of labour in farming.

Direct-seed rice (DSR), which is a technique that involves seed sowing in the main field, has now become the major option, replacing the nursery and transplantations. There were two main types of DSR: dry direct seeding (in which seed is sown into dry or moist soil and then irrigated) and wet direct seeding (in which pre-germinated seed is broadcast or drilled into puddled or saturated soil). They both significantly decrease the amount of water needed compared to transplanting, primarily because they do not require a puddling and need only episodic watering in early establishment, and also have labor savings because raising seedlings and manually transplanted establishment are eliminated. Some recent field trials have been done to compare performance between direct-seeded and transplanted rice that show that under favorable conditions yield is able to be matched or even bettered while water productivity is much greater in the former.

All the above are not considered without conditions. Poor seed-soil contact, early season moisture irregularities and uneven land levelings are more detrimental to DSR establishment, making patchy stands more common. The most consistent agronomic limitation is weed pressure; the weed pressure on DSR fields is high in the absence of water cover as in the case of transplanted fields, and yield loss could be significant if weed control is poor. It is very important to integrate weed management (in addition to establishment method) with stale seedbeds, pre-emergence herbicides, and well-timed post-emergence activities (and if possible, mechanical weeding) as the critical components to achieve DSR success. Based on the evidence, it is clear that using DSR is not always the best alternative to transplanting and that, in specific cases, the choice of DSR or transplanting should be subject to "winners take all" assessment, based on availability of water, soil type, labour costs and the ability to manage weeds, and where feasible, the advantages of DSR are worth its implementation cost only if it is considered a superior resource-saving option to transplanting in that particular situation.

Water and Nutrient Management

The connection between water and nutrient management is intimate in rice and the integration of these aspects is now the focus of recent research, instead of considering them separately as agronomic activities. Alternate wetting and drying (AWD) is the most widely promoted water-saving irrigation technology which dictates when fields are reflooded based on a set threshold for targeting the drying when irrigating dry areas to avoid continuous saturation. A comprehensive review of irrigation technologies in rice is essential to confirm that water-saving technologies under AWD can significantly increase water productivity with proportional reductions in yield, if used properly by defining the drying threshold with care to ensure no undue water moisture stress during critical growth stages like flowering (Mallareddy et al., 2023). With irrigation scheduling decisions made on the soil moisture management plan based on monitoring soil moisture, not on a set date, these water savings are also increased in reliability across varying seasons and soil types.

The principle of nutrient management has also been setup along similarly parallel lines: where blanket fertilizer recommendations are given, a new concept has emerged of site-specific nutrient management (SSNM) which aims to match the nutrient deficiency (gap) in a particular field with the nutrients applied via fertilization. Positive impacts of SSNM approaches have been demonstrated through better rice yields, farm profit and nitrogen-use efficiency and minimising nitrogen losses to the environment, which have been synchronously achieved using improved approaches that have been developing over over 20 years and are now being increasingly supported by the use of digital 'decision-support' tools like Nutrient Expert and RiceAdvice (Chivenge et al., 2021). This is important since nitrogen-use efficiency in the field production of rice under conventional blanket dose approach has remained consistently low with a considerable portion of the added nitrogen loss, mainly through volatilization, leaching and denitrification. To maintain soil organic carbon and soils' long term soil health, integrated nutrient management (INM), in combination with organic fertilizers like farmyard manure with optimized inorganic nutrient doses is an alternative way to package the improvement of NUE. Better nitrogen use efficiency (NUE) fertilizers, such as slow-release and nitrification-inhibitor coated urea, can also help lower N losses by ensuring the nutrients are delivered to the plant in time, especially when using water-saving irrigation systems where soil anaerobic and aerobic conditions change more often than under continuous flooding.

Water and nutrient management do interact very strongly, and that is certainly one of the major points that needs to be understood. With aerobic and anaerobic conditions being alternated, the transformation processes of the soil nitrogen and associated losses change from those of the continuously flooded systems: N application timing and form must be adjusted to, rather than maintained the same as in convention. A split application of nitrogen in synchrony with critical growth phases and/or top-dressing based on a leaf colour chart and/or a nitrogen-demand assessment index of SPAD enables the application of fertiliser to fulfil the actual needs of the crop in a variable water regime. The evidence is largely pointing towards a more integrated approach to water-nutrient management rather than maximising the productivity of one of the input systems or the other, as the windows for increasing water productivity are best captured when there is an synchronisation of nutrient input where the water-saving irrigation generates a soil environment that raises the level of nutrient uptake.

Climate-Smart and Low-Emission Rice Production

Rice is vulnerable to an unpredictable climate, including loss of vegetative and reproductive stage due to drought, loss of spikelet fertility at flowering time due to heat stress, lowland and coastal reduction by progressive flooding and transient flooding (flashfloods), and yield reduction due to salinization of soils and scarcity of freshwater in deltaic areas. Meanwhile, rice cultivation is another major contributor to greenhouse gases, with continuously flooded rice fields producing large amounts of methane because of the anaerobic soil conditions which encourage the formation of methane, and nitrogen management practices also having an impact on nitrous oxide emissions.

The water management that is at the core of strategies for rice greenhouse-gas mitigation. A recent global meta-analysis of AWD shows that methane emissions are reduced by ~50% under AWD compared to continuous flooding, but nitrous oxide emissions increase under AWD, reflecting the transition from highly anaerobic to intermittently aerobic conditions in the soil (Zhao et al., 2024). Importantly, the same analysis determined that the rise in N2O is not a sufficient mitigation of the significant decline of methane, meaning that the GHG of each gas (combined) under AWD still results in a significant global warming potential reduction. It is clear from this finding that the mitigation strategy does not necessarily provide gains on all dimensions of impact on the climate, but the total warming benefits and productivity impacts should be viewed on a combined basis not just on any single gas or impact. In addition, the size that methane would actually be reduced varies depending on how deeply and long into the soil the drying took place, how many times the soil was dried, and the properties of the soil itself (e.g., the presence of organic carbon, soil texture). This means that there is no one-size-fits-all answer to the question, as methane reductions must be understood as varying across localities depending on the specific soil properties that are affected.

Also, crop residue management has another level of modification with the addition or application of straw to the soil rather than burning it, which can subsequently affect soil carbon dynamics and availability of methane precursors, and in some studies, biochar amendment can be expected to reduce emissions as well as enhance soil quality, although the results of the action depend on soil type and the conditions applied during the carbonisation process. Incorporating submergence tolerance, drought-avoidance traits, and heat-tolerant flowering physiology and salinity tolerance into the genetic makeup of crops will serve as climate-resilient varieties to complement the agronomic decisions farmers make to withstand shocks and reduce the likelihood of shifts in yield. Sowing windows, alternative sowing times, avoiding established crops during hot (or flood) periods and laser land levelling for better water distribution uniformity enhance resilience further through agronomic adaptation strategies.

Precision Agriculture and Future Technologies

In the field of productivity, profitability and environmental performance, the following tension is recurring: Invasive water-saving management, in order to reduce emissions as much as possible, can reduce yield and farmers' incomes if the preferred levels of drought exposure are unreasonably high, which in turn affects the adoption incentives. To implement the concept of sustainable climate-smart rice production, mitigation interventions, as such, must avoid emissions reduction as an end in itself and be adjusted so that they stay within the neutral (or positive) production-neutral and corporate profit-neutral boundaries.

Precision agriculture technologies have been continuously applied to rice production and are becoming more common tools to implement the concepts of site-specific management practice to the field level. The use of remote sensing platforms like multispectral and hyperspectral sensor attached unmanned aerial vehicles (UAVs) provides non-destructive methods for measuring crop vigour, nitrogen status, water stress and the incidence of pests and diseases over extensive areas and at fine spatial resolution. Recent reviews of developments of machine learning algorithms for precision agriculture using UAV images demonstrates that the use of CNN and associated deep-learning techniques has grown and many different information extraction procedures yield far better accuracy and scalability compared to traditional image processing techniques, including vegetation indices, canopy nitrogen status and yield prediction (Shahi et al., 2022).

To complement aerial platforms, ground-based and in-field sensors like soil moisture probes and canopy reflectance meters deliver localized and continuous data streams that can enable irrigation and fertilization decisions to be triggered locally and in real time. This spatial information can be superimposed on soil maps, topographic and historical yield information to create management zones in fields that would otherwise be data-wise uniform lines in a line of sight. AI and machine learning algorithms are increasingly aiding the interpretation of these multi source datasets, enabling predictive applications like yield forecasting and early pest and disease detection, as well as recommendations for optimized inputs.

Water-saving regimes like AWD can be implemented with greater precision than is possible using manual assessment of the field, through precision irrigation systems that are triggered by soil moisture sensing and weather forecasting to help minimize risks of loss of yield due to over-drying. Likewise, a series of digital decision-support tools for site specific nutrient management convert the principles of SSNM into guidance for fertiliser use across the field, reducing the technical difficulty in adapting SSNM on the ground, and made available by mobile tools to farmers. These technologies are not meant to supersede good agronomic management, but to increase the precision of the water and nutrient management strategy along with the timeliness and scalability in which these strategies can be applied, especially in large and heterogeneous water and nutrient production settings where homogeneous water and nutrient management might not be optimal.

However, some critical deficiencies need to be addressed for more wide-spread use and optimization of sustainable rice production. First, the IWMPs developed for direct-sown rice are not as advanced as those for transplanted rice, and have not yet been optimized for different rice growing systems. Integrated weed management packages must be tailored to the specific rice growing systems, which should not be simply adapted from those used in transplanted rice. Secondly, in particular the management of herbicide resistance is not sufficiently developed. Second, a long-term (more than one season), multi-season study reporting long-term effects of water-saving irrigation on soil health, nutrient dynamics and yield stability is limited; most studies were conducted over one or two seasons. Third, there are interactions between water-saving irrigation and timing of nutrient management, and these needs to be more field quantifiable for various soil climate combinations. Fourth, the methane-nitrous oxide trade-off under different AWD thresholds should also be quantified in each region to create optimal (region by region) drying regimes that reduce the global warming potential. Fifth, there is limited data to document socioeconomic constraints on smallholders in using AWD and SSNM in many rice-growing regions. Sixth, there is a need for participatory research grounded in AI-supported decision-making support systems in smallholder farming systems, taking into account connectivity and illiteracy issues. In addition, agronomic packages, such as those including climate resilient varieties and appropriate water, nutrient and weed management under different agro-ecologies need to be tested in real-location on farms.

Conclusion

Any one intervention will not be sufficient for sustainable rice production in the near future. However, a comprehensive strategy is needed that incorporates an efficient method of establishing crops that takes advantage of local resource conditions, water-use management through irrigation that matches nutrient application, a strong weed management program to support the method of establishment, agronomic practices and varieties designed for a variety of local climates and applications, water and residue management practices that limit emissions, and precision technologies that allow site-specific decision making at scale. The value of no individual practice – be it direct seeding, alternate wetting and drying or site-specific nutrient management – is derived from careful and localised calibration. Further examples of developing sustainable intensification for rice are building up extension strategies and systems, digital infrastructure and farmer incentives as well as continued agronomic and technological interventions; that is, solving sustainable intensification for rice is ultimately a systems-level challenge.

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