

Next-gen rice farming: ways to achieve food, nutritional and economic security under changing climatic conditions

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The present rice cultivation systems face challenges of low production, water scarcity, shrinking cultivable land area due to degradation and urbanization, labour shortage, diminishing soil health, climate change, greenhouse gas emissions and low income for farmers. Changes and/or modifications are thus necessitated in rice production to feed future generations. The aim of next-gen rice farming is to provide food, nutrition and economic security, as well as climate-smart solutions to safeguard ecosystems while using better tools and techniques, improved cultivars and management practices. To achieve these, there is a need to develop suitable farm mechanization for small-sized fields, precision (sensor-based) water-saving irrigation methods, greater input use-efficient systems, digital farming considering soil health improvement and proper utilization of rice straw. Next-gen rice farming should be taken as a business opportunity for the youth to earn more income and must be supported by a favourable Government policy.

Keywords: Alternate wetting and drying, digital farming, farm mechanization, precision irrigation, system of rice intensification.

RICE is the most important food for more than half of the global population (4 billion), which provides 21% of the human per capita energy and 15% of the per capita protein¹. Rice is grown in 114 countries, with a total harvested area of nearly 167 million hectares (m ha), producing more than 755 million tonnes (mt) of paddy annually (504 mt of milled rice)². Globally, it is grown by 144 million farm families (25% of the world's farmers), and the rice produced is valued at US\$ 206 billion. Ninety per cent of the rice produced globally is from Asia, with China and India as the major contributors; 55% of Asian rice comes from these two countries. When comparing these two major rice-growers, the area is greater in India than in China, but rice production is lower. The present data show the productivity of rice in China is nearly double that of India (7.03 compared to 4.06 t ha⁻¹), while the average rice production globally is at 4.68 t ha⁻¹, and the average rice yield in Asia is 4.83 t ha⁻¹ (ref. 2).

To feed an estimated 34% increase in the global population by 2050, there is an urgent need to increase the productivity of rice^{3,4}, and this is challenging. Based on population growth and income projections, global rice

demand is expected to increase from 763 mt in 2020 to 852 mt in 2035, i.e. a 12% increase⁵.

Paddy-growing lands are shrinking because of urbanization, climate change and competition from higher-value crops. Therefore, we need to produce a minimum of 8–10 mt more paddy each year from shrinking areas with an annual increase of 1.2–1.5% to feed the growing world population, keeping prices affordable⁶. Additionally, rice production will face constraints like water scarcity, labour shortage and availability, poor profitability, climate uncertainty, etc. in the future.

Water is vital for life, and only 2.5% of water available on the Earth is fresh, and only 0.1% is available to humans. It is also an indispensable input to agriculture, and globally, 70% of freshwater is used in the agriculture sector^{7,8}. Due to population growth, higher food demand, growing living standards and increased energy (biofuel) production, the use of global freshwater has increased more than sixfold since 1900 (671 billion m³ to 4 trillion m³)⁹. Half of the global population (3.6 billion) is living in water-scarce conditions, and if business continues, this population could increase to 4.8–5.7 billion by 2050 (ref. 10).

In agriculture, conventional paddy production is the largest consumer of water. Nearly 800–5000 litres (average 2500 litres) of water is used to produce 1 kg of rice¹¹, which amounts to 440 billion m³ of irrigation water for growing only rice globally.

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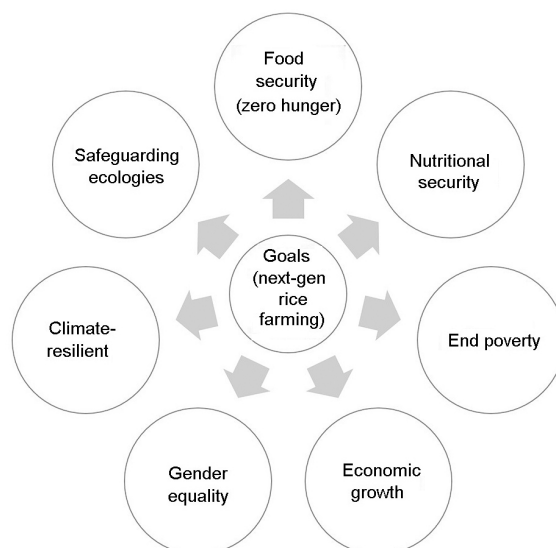


Figure 1. Goals of the next-gen rice farming.

Climate change has intensified the problem of water shortage, which consequently results in the deterioration of water quality, a rise in extreme weather events, a rise in temperature, unreliable rainfall events, etc. To feed the growing population, we need to produce more rice sustainably, i.e. with greater water efficiency (more crop per drop), while making appropriate adjustments to adapt to climate change.

No doubt, rice will remain the key component of the food basket of families, affecting the nutritional and economic security of many countries in the foreseeable future. However, traditional methods for cultivating rice are not sustainable in many parts of the globe, and thus, the way rice is grown must change. We must consider a more efficient rice management system for the future. In this study, we discuss challenges currently and foreseeably faced in rice farming and strategies needed for next-gen rice farming to feed the growing population with nutritious food and to achieve economic security for the rice growers. Overall, the goals of next-gen rice farming should be food, nutritional and economic security, gender equity and climate-smart situations to safeguard rice ecosystems (Figure 1).

To achieve these goals, the strategies should include closing the yield gap; improving input-use efficiencies, especially water and nutrients; using modern tools and techniques; making climate-resilient rice systems; strengthening the value chain and adopting business models/group farming for higher income and support from policies and reforms in the extension system.

Development of new genotypes

Rice varieties having a high yield potential ($10\text{--}15\text{ t ha}^{-1}$) must be developed; a type of super rice tolerant to multiple

biotic and abiotic stresses with high protein content (12% or more), micronutrient-rich (especially Zn and Fe content), and having increased vitamin content (e.g. vitamin A and E) in the grains. These varieties should be of medium duration (120–125 days) so that overall water requirement is minimized and the fields are free to grow other crops. High-yielding aerobic rice varieties with water stress tolerance and disease resistance must be developed.

Also, future rice varieties should be developed based on market demand or consumer preferences. For example, according to the International Diabetes Federation (IDF), approximately 537 million adults had diabetes in 2021, which is expected to increase to 643 million by 2030 and 783 million by 2045 (ref. 12). This diabetic population lives mostly (~75%) in low- and middle-income rice-consuming countries. Therefore, rice varieties having low glycemic index (GI) should be developed to control blood sugar levels to prevent and control diabetes among rice-eaters.

Globally, rice cooking consumes a huge amount of energy. Therefore, energy conservation in rice cooking is an essential area of scientific research. A total of 405–2880 kJ energy is required to cook 1 kg of rice depending on the nature of cooking, appliances used, heat source, varieties, parboiled or normal, use of pre-soaked or unsoaked rice, etc.^{13,14}. Developing rice varieties with low gelatinization temperatures could reduce cooking time, save energy, and contribute to the reduction of toxic emissions for the benefit of environmental and human health.

Presently, low nutrient use efficiency (NUE) for nitrogen (35–40%) and phosphorus (20–25%) in flooded rice is a major concern. To reduce the cost of cultivation and environmental pollution, varieties and management practices must be developed to increase fertilizer use efficiency. For example, to improve NUE and reduce external nitrogen application for the rice crop, new plant types must be

engineered with the *nif* gene from legumes to fix atmospheric nitrogen. Also, site-specific nutrient application using soil health cards or leaf colour charts for nitrogen application should be in practice. From the management point of view, the use of slow nutrient-releasing fertilizers, nano-fertilizers, proper water management practices, etc. must be in practice in future rice cultivation.

Farm mechanization

In India, the total number of agricultural workers (cultivators and labourers) increased from 234.1 million in 2001 to 263.1 million in 2011. However, the share of the workforce engaged in the agriculture sector decreased from 58.2% in 2001 to 54.6% in 2011, mainly due to the migration of agricultural labour from rural to urban areas¹⁵. Therefore, agriculture in totality, particularly rice cultivation, faces labour shortage and availability on time, especially during transplanting, harvesting and post-harvest operations in most rice-growing countries.

To sustain rice cultivation in the future with minimum use of manual labour for all the farm activities, starting from land preparation to harvesting, post-harvest processing and marketing, we may have to depend on farm machinery. Automation in farm mechanization helps reduce input use and manual labour demand. Most rice fields in Asian countries are small and fragmented; therefore, we need to develop and use 'mini' machines powered by solar-charged batteries to conserve energy and benefit the environment. To be precise in the application and for greater efficacy, nano-formulations of fertilizers and nano-bio-pesticides should be used, adopting variable rate technique (VRT) with the help of sensor-based unmanned aerial vehicles (UAVs) like agricultural drones.

Precision irrigation and nutrient application

To sustain rice cultivation in the future, we need to use efficient water-saving irrigation methods. Water application to the crop through irrigation should match crop evapotranspiration (ET_c) (~600 mm) by adopting precision irrigation methods like sensor-based micro-irrigation and/or alternate wetting and drying (AWD) or any other efficient irrigation method with VRT.

In India, 29.37 mt of fertilizers were used in 2019–20 (ref. 16). Excess and untimely use of chemical fertilizers in rice not only makes it inefficient but also pollutes water bodies and the environment. For example, presently, nitrogen and phosphorus use efficiencies in rice are 35–40% and 20–25% respectively. To make rice cultivation an efficient and profitable production system, the input use efficiencies have to be increased from the current levels by deploying modern and efficient technologies. The nutrient application should match the crop demand, and it could be applied based on soil testing, using customized leaf colour charts

and other technologies. Coated fertilizers (neem-coated urea), nano-fertilizers and nano-formulations of macro- and micro-nutrients are some options that could be applied in low doses with greater efficiency. Top-dressing of fertilizers should be done using drones or VRT. Recently, Zhu *et al.*¹⁷ found that deep placement of mixed urea through a machine and controlled-release urea at the time of transplanting is highly efficient in increasing the yield, improving NUE and reducing the amount of applied N-fertilizers. Instead of chemical herbicides, bio-herbicides for weed management may be preferred to reduce soil health damage.

Rice straw/residue management and post-harvest processing of grains

Rice cultivation generates a large quantity of crop residues (roots, stubbles and straw) in the field after harvesting. An estimate shows that every year, 242 mt of rice straw is produced in China and 97 mt in India¹⁸. Rice straw is either spread in the field, collected in heaps, or sold for other purposes. However, in Asian countries, rice straw is mostly burnt in the field because of its cost-effectiveness and requires less labour than incorporation into the soil¹⁹. Further, the burning of rice straw has benefits in the ease of farm operations but is harmful to the environment. Open-burning of rice straw in the field emits a large amount of pollutants²⁰, contributes to global warming through emissions of greenhouse gases (GHGs)²¹, and noticeably contributes to the formation of atmospheric brown cloud that negatively affects the air quality of local areas, atmospheric visibility, and climate²². This straw burning also eliminates many pathogens and causes loss of several nutrients²³. Furthermore, biomass burning is one of the largest sources of primary fine carbonaceous particles in the global troposphere and the second largest trace gases^{24,25}.

The quantity and quality of rice straw incorporated into the soil are important for increasing soil organic carbon (SOC) and potassium-management strategies²⁶. Straw incorporation can significantly increase SOC storage^{27,28} and available K content^{26,29}, as well as help mitigate climate change^{30,31}. A long-term study showed that 10 years of rice straw incorporation into the fields significantly increased the SOC content, but in the short term (1–2 years), straw incorporation had no positive effect on SOC³². Yuan *et al.*³³ reported that rice straw incorporation along with K-fertilizer application is the best practice for improving crop productivity and soil fertility in the rice–wheat cropping system. To ease straw incorporation, the harvester should cut it into small pieces and mechanically incorporate it into the soil.

There is a range of uses for rice straw and husk, and several valuable products can be made from them. These include agricultural use (composting using bioagents, forage to feed livestock, mulching, mushroom production), energy generation (biodiesel, and production of alcohol, biogas

and bio-oil), environmental adsorbents (biochars and activated carbon), construction materials (building products, ash as pozzolans), speciality products (silica, celluloses, textile, paper and cardboard, organic chemicals, bioplastics), biological control agents (algal control, insecticides), and many more^{34–37}. Farmers and local people could be involved in rice-straw bioenergy development for sustainable bioenergy systems and improving income along with environmental benefits³⁸. Additionally, a policy of rural development with Government support is essential to make alternative uses of rice straw more attractive so that rice straw burning will be progressively phased out in the future.

Post-harvest processing of rice is another area that needs to be considered for improving the income of rice growers. In several countries, individual rice farmers outsource services from the owners of agricultural machines for tilling, sowing/transplanting, harvesting and milling. In India, 68% of operational land holdings belong to marginal farmers having an average land holding of 0.38 ha size¹⁶. Therefore, operating large machines for farm operations at the field level is difficult. A study also showed that the use of a combine harvester and mechanical reaping/winnowing caused greater harvest loss than manual harvesting³⁹. It also reported that the losses were higher in segmented harvesting than in combine harvesting. Therefore, there is a need to develop cheaper and smaller machines suitable for smallholders. To achieve food security and higher income for the farmers, on-site processing of grains, rice milling, and packaging should be made feasible at the grower's level; that is, 'field to plate' should be local. There is also a need to develop processing techniques that should add value to low-grade rice and help in fetching higher prices in the market.

Rice farmers face several problems in production, viz. low yields, poor grain quality and low sales, leading to low profitability. To address these problems, the group-based farming approach in rice cultivation has several advantages, viz. efficient learning of improved cultivation techniques in a group through sharing of experiences, ideas and discussions, aversion of risks, improved access to funding for agricultural inputs and costly machinery and a greater role for marketing of produce, achieving stronger bargaining power and higher income⁴⁰.

Rice cultivation with reducing greenhouse gases

Globally, agriculture is contributing to 24% of GHG emissions⁴¹ and 14% of anthropogenic GHG emissions in the form of methane (CH₄) and nitrous oxide (N₂O)⁴². Paddy cultivation is one of the greatest sources of anthropogenic GHG emissions, mainly N₂O, CH₄ and carbon dioxide (CO₂)⁴³, contributes 9–11% of the agricultural GHG emissions⁴², and is one of the factors responsible for climate change⁴⁴. Nearly 30% of global agricultural CH₄ emissions and 11% of N₂O emissions come from the paddy fields^{45–47}.

Two crucial components in rice cultivation that are responsible for GHG emissions are water and nutrient (nitrogen) management. Conventional practices of rice cultivation include continuous flooding and the application of large amounts of fertilizer to get more grain yield; at the same time, it produces enormous amounts of CH₄ due to an anaerobic soil environment^{48,49}. To fulfil the projected higher demand (production) of rice, an increased application of water and fertilizers might be required, and this will again lead to increased GHGs in the future^{43,50}. Therefore, a different approach to rice cultivation is needed, which must require less water, use nutrients (nitrogen) with greater efficiency, produce more grains and be climate-smart to minimize GHG emissions. Therefore, a multi-dimensional approach for future rice cultivation is warranted to address all these complex issues.

Studies have suggested that emissions of N₂O are linked with nitrogen fertilizer application, which occurs mostly in dry land (aerobic) conditions⁴³ while flooded rice fields (anaerobic) are a major source of CH₄ and contribute little to N₂O emissions^{51–53}. Moreover, CH₄ emissions vary across agro-climates (rice-growing seasons), soil types, the difference in SOC, etc.^{54,55}.

Several strategies for mitigating CH₄ emissions from paddy cultivation have been reported as an effective way to mitigate the global warming potential (GWP)^{56,57}. Strategies to mitigate CH₄ emission from rice fields include water management practices like promoting intermittent drainage, AWD^{46,58–61}, micro-irrigation, the system of rice intensification (SRI)^{62–64}; organic management by composting, application of fermented manure (biogas slurry)⁶⁵, using slow-releasing neem-coated urea, growing rice cultivars having few unproductive tillers, greater root growth and high harvest index⁶⁶ and direct-seeding rice (DSR)⁶⁷.

Researchers have reported that AWD is an effective way of saving water (by 50%); it reduces the net GWP from rice fields (by 46–63%) along with a slight increase in grain yield over that of continuous flooding^{46,58}. SRI promotes keeping rice fields unflooded or AWD, using organic fertilizers over chemicals, along with other modifications in crop management^{68,69}. Under SRI, effective nutrient management coupled with AWD irrigation^{70, 71} could significantly reduce GWP^{58,63,72,73}. Recent research from Africa confirms that SRI reduces CH₄ and CO₂ emissions by 59.8% and 20.1% over conventional flooded rice, respectively and overall, it reduces GWP without compromising rice yield⁶⁴.

The SRI method was tested in various countries and found to significantly enhance yield⁷⁴, save water^{75,76} and reduce GHG emissions^{63,77}. It also has several other benefits like climate adaptation under biotic and abiotic stresses⁷⁸, enhancing the income of farmers^{79,80} and achieving the United Nations (UN) Sustainable Development Goals (SDGs)⁸¹. However, its adoption and benefits depend on several factors, like proper training reported from Bangladesh⁸², labour shortage and water constraints in Cambodia⁸³,

etc. Unfortunately, support from the Governments, policy-makers, donor agencies, research institutions and a few researchers for the promotion of SRI is lacking.

Digital rice farming approach

New technologies and digitalization have started transforming agriculture in developed countries. Developing countries like India have also started promoting new-generation technologies or digital technologies in agriculture to offer new opportunities to the rural youth. The world's first fully machine-operated spring barley crop was harvested in 2017 at Harper Adams University, UK, without a human ever entering the field, a milestone in digital agriculture (sometimes called 'smart farming' or 'e-agriculture'; https://www.business-standard.com/article/pti-stories/world-s-first-robotic-farm-completes-fully-automatic-harvest-117100200475_1.html).

Digital farming includes technologies like the Internet, mobile apps, data analytics, artificial intelligence, internet of things (IoT), drones, robotics, sensors, digitally-delivered services, etc.⁸⁴. These technologies in rice farming could be applied at different stages of crop production, processing and marketing. For example, farmers could plan sowing or transplanting based on weather forecasting and mobile app-based agro-advisories. Using remote sensing data and *in situ* sensors (soil moisture or nutrients) linked to mobile apps improves precision in the application of water and/or nutrients, saves time, reduces wastage of these critical inputs, and benefits soil health and the environment. Solar-operated, sensor-based drip/sprinkler irrigation has the potential to save water in rice cultivation. The use of drones in rice farming has the potential to monitor disease/pest attacks and their control, nutrient application, etc. Digital logistics services with mobile apps for marketing rice offer the potential to streamline supply chains, linkage and trust between producers/farmers and consumers. Overall, digital technologies in rice farming would improve production, reduce the cost of cultivation/processing/marketing, increase profit and benefit the environment. Advancements in these technologies can help achieve several SDGs of the UN.

Conclusion and policy

For next-gen rice farming, policy support from the Government is essential. For example, to harvest the benefits of digital rice farming, few actions are required, viz. forming Government policies and programmes to facilitate the adoption of digital technologies and developing supportive digital infrastructure; the Government should also invest along with other partners to facilitate human resource development/training to develop skills among the farmers regarding digital farming. Policy support is required to adopt climate-smart technologies like SRI⁷⁸, natural farming⁸⁵, organic

farming⁸⁶ or improved irrigation methods like AWD or micro-irrigation^{71,87}. Water application in rice production is very high; therefore, nominal water pricing should be implemented, and a reward system for the farmers using less water to grow rice should be implemented by the Government.

All the inputs required for next-gen rice farming, SRI, organic or natural farming with quality assurance should be available at the local level or at the farmer's doorstep. The Government is providing subsidies on many agricultural inputs like farm implements and micro-irrigation systems, and the benefits of these are usually availed by rich farmers. A policy should be operational on subsidies percentage considering the income of the farmers, and poor/landless farmers should get more subsidies than the rich farmers. Policy support is also required to ensure premium prices for the rice grown using organic or natural farming or organic SRI.

Climate change is causing many extreme events, such as erratic rainfall, cyclones, droughts, and floods. Self-insurance by adopting crop diversification or an integrated farming system is insufficient for rice-growers. Therefore, an insurance model with easy financial support and payments to farmers as compensation should be designed and developed in case of crop damage due to extreme events⁸⁸.

A reform in the extension system is required for training on modern tools/techniques, empowering women in decision-making, and market/demand analyses. Its incorporation in developing speciality rice/rice products and adoption of improved technologies in paddy cultivation play a crucial role in the next-gen rice farming system. A strong linkage among rice-growers (including women), extension functionaries, researchers, marketing managers, funding supporters, customers and business developers in the development of varieties (demand-driven) and improved technologies; adoption of modern tools and techniques; value addition and marketing of produce; promotion of indigenous rice varieties having premium quality, etc. play a crucial role in shifting from conventional rice farming to the next-gen rice farming. Overall, a need for transformation in rice farming from a subsistence to a business model through group farming or forming co-operatives or farmer producer organizations or start-ups is a requisite for higher income of the farmers. For this, suitable policy formulations by the Government are needed to attract the youth and farmers towards rice farming as an employment to earn more income through business development.

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