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A REGIONAL STRATEGY FOR SUSTAINABLE HYBRID RICE DEVELOPMENT IN ASIA

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
REGIONAL OFFICE FOR ASIA AND THE PACIFIC
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FOREWORD

Hybrid rice has been cultivated for almost 40 years in China and nearly 20 years in several Asian countries. As projected, rice production in the world and Asia should increase further in the years to come to meet the consumption demand of growing population, including those in Africa and other regions, while there has been a stagnation or decline in the total area of arable lands. Therefore, rice production increase needs to rely on rice productivity enhancement from existing agricultural lands. It is believed that due to recent advances in scientific and technological innovations, a new generation of rice hybrids could break the rice yield plateau. It has demonstrated that hybrid rice could increase rice yield by 15-20 percent and would contribute substantially to future rice yield increase, if adopted widely. However, except China where hybrid rice shares over 50 percent of total rice growing areas, the impact of hybrid rice has been still very limited in other countries with the share less than 10 percent. We found that one of potential causes of slow expansion of hybrid rice is a lack of sufficient effort for creating an enabling environment to smallholder farmers to take decision to adopt this new technology, due to high cost of hybrid rice seeds, difficulty to produce hybrid rice seeds locally, high economic risks if failed in the production, and other reasons. Obviously, we need to remove these bottle necks to accelerate hybrid rice development. These call for a need for an appraisal of the hybrid rice sector in Asia and identify a strategy and road map for the future development.

Under these backdrops, a Regional Expert Consultation on "Hybrid rice development in Asia: Assessment of limitations and potential" was jointly organized by the FAO Regional Office for Asia and the Pacific (FAORAP) and the Asia-Pacific Seed Association (APSA) on 2-3 July, 2014, in Bangkok, Thailand, attended by the representatives from 14 countries in the region and more than 70 hybrid rice specialists, policy makers and private sector representatives, to discuss the status and prospects of hybrid rice development in Asia. Based on the outputs of the Consultation, FAO spearheaded the formulation "A Regional Strategy for Sustainable Hybrid Rice Development in Asia" with the contribution of all those attended the consultation meeting as well as those experts from FAO, IRRI, APSA, IFPRI and other national institutions. The strategy document was endorsed by the country representatives and other participants who attended the Consultation Meeting.

In this opportunity, I wish to convey my gratitude to all those contributed to the finalization of the strategy document, including Dr. Bui Ba Bong, FAO Senior Agricultural Officer (Rice Expert).

I am honored to present the Regional Hybrid Rice Strategy and sincerely hope that this strategy will be helpful in providing strategic directions and options for various stakeholders including smallholder farmers in the region towards promoting sustainable hybrid rice development, and contributing to regional and global food security.

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FAO Regional Office for Asia and the Pacific

ACRONYMS

APSA	Asia-Pacific Seed Association
ASEAN	Association of South East Asian Nations
AWD	Alternate wetting and drying
CMS	Cytoplasmic male sterility
FAORAP	FAO Regional Office for Asia and the Pacific
HDRC	Hybrid Rice Development Consortium
ICT	Information and Communication Technology
IFPRI	International Food Policy Research Institute
INM	Integrated nutrient management
IPM	Integrated pest management
IPR	Intellectual property right
IRRI	International Rice Research Institute
ISF	International Seed Federation
MAS	Marker assisted selection
MDG	Millennium Development Goals
NGO	Non-government organization
PGMS	Photoperiod sensitive genic male sterility
PPP	Public-private partnership
PVP	Plant Variety Protection
QTL	Quantitative trait loci
SAARC	South Asian Association for Regional Cooperation
TGMS	Thermo-sensitive genic male sterility
UPOV	Protection of New Varieties of Plants ISF
WA	"Wild abortive"

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EXECUTIVE SUMMARY

Rice plays an important role in ensuring food security and contributes to the alleviation of poverty and malnutrition in Asia and the world. As the world's population continues to increase, there will be further demand on rice supply to meet additional consumption. Because the potential for expanding rice area is almost exhausted, the increase of rice production would be achieved by raising the productivity level mainly. The adoption of rice hybrids on a commercial scale has been identified as a means to further raise the yield potential by exploiting the genetic expression of heterosis or hybrid vigor. In the backdrop of the hybrid rice development in Asia in the last decades, a regional strategy for sustainable development of hybrid rice in Asia was formulated to provide evidence-based strategic guidelines and options to countries that would like to formulate or reorient the strategies and programs of hybrid rice development in their countries.

OVERVIEW OF RICE SECTOR DEVELOPMENT IN ASIA

Rice is one of the most widely grown crops in the world, providing food for half of the world's population. In all of Asia, rice is the staple food grain, accounting for approximately 30 percent of daily caloric intake. Additionally, more than 140 million rice-farming households rely on rice as their primary source of livelihood. Asia contributes up to 88 percent and 91 percent of the world's rice area and production, respectively. From the start of the 21st century to date, the rice production in Asia has increased unceasingly to obtain additional 130 million tons or 10 million tons per year. Therefore, through both cultivation and consumption, rice plays a central role in the food and livelihood security of millions of households across Asia.

Despite those significant achievements in rice production attained in Asia during the last 10 years, a number of challenges and uncertainties have been foreseen to affect rice production adversely in the years to come, including (*a*) high incidence of hunger and poverty in the region; (*b*) shrinkage of essential resources for rice production such as land, water, and labor; (*c*) increase of population and food demand; (*d*) declined trend in rice productivity growth; (*e*) environmental degradation caused by mismanagement of agronomic practices in rice production; and (*f*) effects of climate change.

In the face of all these challenges, several new opportunities have emerged to support a sustainable development of the rice sector in the years to come. These opportunities could be enumerated as (*a*) strong commitments of the world community to eliminate hunger and poverty in the post-2015 Development Agenda; (*b*) fast development in technological innovations in agriculture crops, particularly rice; (*c*) concerted efforts and commitments at global and country levels to cope with climate change on agriculture; and (*d*) transformation of the rice sector in many rice-growing countries.

STATUS OF HYBRID RICE DEVELOPMENT IN ASIA

Progress in hybrid rice development

China was the first country to start research on hybrid rice in 1964 and commercial production 12 years later. Subsequently, the release of improved new hybrids every year accelerated a speedy increase in the planting area of hybrid rice in China, reaching to a peak of 60 percent of the total rice area of 30 million hectares. Chinese scientists have continuously created innovations in hybrid rice technology leading to the successful development of two-line hybrids and recently "super hybrid rice". Outside China, several Asian countries started their hybrid rice research programs in the 1980s or early 1990s. As a result, the total hybrid rice area outside China has reached 4.5 million hectares distributed in India, Vietnam, Indonesia, Bangladesh, the Philippines, Pakistan, and Myanmar.

Constraints and opportunities in hybrid rice development

Several constraints affecting the low pace of adoption of hybrid rice outside China include (*a*) the lack of rice hybrids specifically adapted to various geographically disparate agro-ecological conditions; *(b)* low heterosis magnitude and narrow genetic diversity of parental lines; (*c*) low hybrid seed production yields; (*d*) improper crop management practices; (*e*) farmers' limited resource capability and the price volatility of paddy; and (*f*) inadequate public investment in hybrid rice research and development (R&D).

Despite these challenges, new opportunities have opened up for a sustainable hybrid rice development in the future. Rice-growing countries have been looking for alternatives to improve rice productivity either to lessen the dependence on rice imports and approach to self-sufficiency or to enhance and consolidate rice exports. The advancements of molecular biology, genomics, and biotechnology have resulted in significant improvement in hybrid rice breeding. Furthermore, the technologies for hybrid rice seed production have been refined and improved in recent years. There has been an increasing trend in public-private partnership (PPP) and increased investments by the private sector for R&D of hybrid rice.

STRATEGY OF SUSTAINABLE HYBRID RICE DEVELOPMENT IN ASIA

Vision for hybrid rice development

In view of the progress, challenges, and opportunities in hybrid rice development in Asia and under the direction of the regional rice strategy, the vision of sustainable hybrid rice development in Asia toward 2030 is that of *substantial and sustained increase of rice productivity in both irrigated and rainfed ecosystems contributing to food security, poverty reduction, and hunger elimination, and shared benefits amongst rice farmers - particularly smallholders, consumers, and the business sector in the region*.

With the advent of new opportunities, particularly innovations in science and technology, hybrid rice is expected to play a major role in breaking the current yield plateau and thus contributing to sustainable food security. In an increasingly competitive environment, the higher productivity of hybrid rice will also improve the profitability and attractiveness of rice cultivation.

To turn the vision to reality, strategic objectives (SOs) and key themes and options are proposed, as follows.

Strategic objectives

The following four key SOs are selected to achieve results from the vision and the future opportunities of hybrid rice discussed above.

SO1: To obtain higher productivity from hybrid rice with accepted grain quality

Rice hybrids should first attain higher productivity than conventional varieties under the same agro-ecological and management conditions. In addition, in order for hybrid rice cultivation to prove a profitable venture for most farmers, the grain quality of hybrids must be sufficient to satisfy end consumers. Therefore, grain quality preferred by target consumers and the market should become an added objective along with high yield in hybrid rice development.

SO2: Adoption of hybrid rice on a large scale in various ecosystems by a large number of farmers

The impact of hybrid rice would be more significant and noteworthy if its application scale can be expanded to a large number of farmers in various ecosystems. Therefore, scaling-up of hybrid rice adoption should be a key objective in hybrid rice development in future.

SO3: Promotion of the private sector in hybrid rice development

As the main producer and supplier of hybrid seeds, the private sector plays a crucial role in hybrid rice development. In addition, the private sector is also involved in R&D of hybrid rice. Thus, the role of the private sector should be promoted through seemly and conducive policies and the effectual PPP.

SO4: Enhancement of benefits to rural community and smallholder farmers

Apart from the impact on food security, hybrid rice should also bring in socioeconomic benefits to rural community and smallholder farmers to sustain hybrid rice development. This calls for innovative approaches to strengthen the capability of the community and to make hybrid rice receptive to smallholder and resource-poor farmers.

Key themes and options

To translate the above SOs into activities and programs, the following key themes and options are suggested.

Improvement of rice hybrids adapted to various ecosystems and climatic change

To broaden the genetic diversity of cytoplasmic male sterile (CMS) sources, it is worthwhile to search for different new CMS sources. Generally, the most important attributes of male sterile lines that affect the performance of the resulting hybrids include high heterosis, high out-crossing rate, good grain quality, and resistance to major diseases and pests. Research on super hybrids linked to inter-subspecific breeding and two-line hybrid rice system based on thermo-sensitive genic male sterility (TGMS) should also be given a priority in the years to come. Primarily, high yield combined with high hybrid seed production potential and suitable quality is a desirable trait combination required in a hybrid rice variety. Besides, depending on the local conditions, other traits should be incorporated in the hybrid, for example, disease and insect pest resistance, tolerance to abiotic stresses, higher efficiency use of resource, adaptation to rainfed conditions or direct seeding system, and suitable growth duration.

Improvement of hybrid rice seed production and supply

The availability of hybrid seeds at affordable price to farmers is the most important determinant of hybrid rice development. To ensure sufficient hybrid seed supply, countries growing hybrid rice should establish and strengthen their domestic hybrid rice seed industry through suitable mechanisms such as (*a*) the active involvement of the private sector; (*b*) technology innovations to increase hybrid seed yield and quality; (*c*) seed certification and quality control; and (*d*) marketing and trade promotion of hybrid seeds.

Optimization of crop management practices of hybrid rice production

The productivity of a hybrid variety depends not only on its genetic potential but also on the crop management practices. The crop management practices for hybrid production should be suited to the rice ecosystems, production systems, local conditions, and specially the hybrid genotype and should follow the principles and good agronomic practices of sustainable crop intensification as promoted by FAO under the banner of "Save and Grow" and "Climate-Smart Agriculture".

Support of smallholder farmers for hybrid rice adoption

In order to promote the participation of smallholder farmers in hybrid rice production, it would be important to provide public support at the initial stage of hybrid rice introduction, which may include (i) subsidy to hybrid rice seeds in a limited period; (ii) provision of credits; (iii) training of smallholder farmers in hybrid rice cultivation and hybrid rice seed production; (iv) facilitation of community-based hybrid rice seed production programs; (v) promotion of market information systems and expansion of hybrid rice market; (vi) introduction of subsidy (or support) to crop insurance scheme, and (vii) investment for improving infrastructure bases at community level.

Strengthening extension and technology transfer for hybrid rice adoption

Effectual extension systems would help accelerate the pace of hybrid rice adoption by farmers and make sure that the technology is sustainable at the community level and farmers' fields. Capability building, particularly human resource development is a prerequisite to establish a soundly organized extension system. The extension approach of Farmer Field School (FFS) appears highly appropriate to induce farmers to be proactive in technology adoption. Women should be empowered through training to actively be involved in hybrid rice cultivation and seed production. Modernization of the value chain of the hybrid rice industry could attract more young farmers to engage in hybrid rice production or seed business.

Facilitating the establishment of mutually-beneficial public-private partnership

PPP is a backbone in hybrid rice development because of the indispensable linkages of technology generation, diffusion, and commercialization of products. Therefore, an effective partnership would bring together the distinct strengths of public and private sectors to attain the common goal. Specifically, governments should support the exchange or licensing of germplasm and other breeding materials among stakeholders and between countries, protect intellectual property rights (IPR), and streamline technological procedures and standards.

National coordination mechanisms and international cooperation on hybrid rice development

A national platform for hybrid rice development would provide a mechanism to synergize the activities of various stakeholders engaging in the hybrid rice industry including public and private agencies, NGOs and civil organizations, local communities, and farmers. At the international level, hybrid rice R&D cooperation and networking should be maintained and strengthened through international platform for hybrid rice development. Beside international cooperation, South-South cooperation under the assistance of FAO would be a suitable mechanism to disseminate hybrid rice between countries in Asia.

Policy options for hybrid rice technology innovations and commercial adoption

Policy options should be focused on improving and enhancing the national strengths in hybrid rice technology innovations and commercialization. First, increased investment in R&D and E (extension) for hybrid rice should be firmly committed and implemented by the governments to build up national capacity in human resources and infrastructure to enable the development and dissemination of hybrid rice technologies. Second, the governments should provide incentives for the private sector to engage in the hybrid rice industry, particularly to improve the capability and efficiency of domestic hybrid seed production system and technology transfer. Third, policy options should be focused on improving the conditions at the community level and smallholder farmers to become more receptive to hybrid rice technology.

BACKGROUND AND APPROACH

Rice is the staple food of about half the world's population, of which more than 90 percent of the rice consumers inhabit in Asia. Therefore, rice plays an important role in ensuring food security and contributes to the alleviation of poverty and malnutrition in Asia and the world. It is projected that as the world's population continues to increase, there will be further demand on rice supply to meet additional consumption. Because the option of expansion of rice area is almost exhausted, increase in rice production would be mainly achieved by raising the productivity level. Nevertheless, the challenge is that the growth of rice productivity has stagnated or even declined in recent years because of marginal improvement in the rice yield potential.

To overcome this challenge, the application of rice hybrids has been demonstrated as a means to raise further the rice yield potential by exploiting the genetic expression of heterosis or hybrid vigor. Although the incredible success of hybrid rice adoption has been achieved in China, the pace of diffusion of hybrid rice technology in other countries has been acutely low or stagnant for a long time and confined only in a few countries in Asia where nearly about 90 percent of the world's rice is produced. In view of the backdrop of hybrid rice development in the recent years, the FAO Regional Office for Asia and the Pacific (FAORAP) and the Asia-Pacific Seed Association (APSA) jointly organized a regional expert consultation on "Hybrid rice development in Asia: Assessment of limitations and potential" on July 2–3, 2014, in Bangkok, Thailand. The consultation, which was attended by a large number of policy makers and representatives from public institutions in 15 countries and entrepreneurs from 30 private seed companies, analyzed painstakingly the status and prospects of hybrid rice development in Asia under emerging issues and challenges in rice production. Subsequently, based on these deliberations, a regional strategy for sustainable development of hybrid rice in Asia was formulated by FAORAP with the consents of member countries. The strategy aimed at providing evidence-based strategic guidelines and options to member countries that would like to formulate or reorient the strategy and programs of hybrid rice development in their respective countries.

OVERVIEW OF RICE SECTOR DEVELOPMENT IN ASIA

Rice is one of the most widely grown crops in the world, providing food for half of the world's population. In all of Asia, rice is the staple food grain accounting for approximately 30 percent of daily caloric intake, and in several countries in South and Southeast Asia, the calorie intake derived from rice is more than 50 percent. Therefore, rice plays a central role in ensuring the food security of Asia. Further, more than 140 million rice-farming households rely on rice as their primary source of livelihood.

Worldwide, rice is being cultivated on 166 million hectares of land, producing 745 million tons of rough rice at an average productivity of 4.48 tons per hectare (FAOSTAT 2013), and Asia contributes up to 88 percent and 91 percent of the world's rice area and production, respectively. Rice in Asia is predominantly produced on millions of small family farms with an average size of 1 hectare per household.

Across Asia, rice is cultivated in the three main ecosystems defined by water supply and control, namely, irrigated, rainfed lowland (including deep water and flood-prone areas), and rainfed upland, constituting 60 percent, 34 percent, and 6 percent of the total rice area, respectively. Among countries, the distribution of these ecosystems diverges because of differences in water resources, geographic conditions, and government investment in irrigation infrastructure. Certain countries have a high percentage of irrigated area extending above 90 percent of the total rice area, whereas other countries still have less than 30 percent of the total rice area under irrigation.

From the start of the 21st century to date, the rice area, yield, and production in Asia have increased unceasingly to obtain further 10 million hectares and 0.63 tons added per hectare, giving rise to an increase in production of 130 million tons or 10 million tons per year. These accomplishments have enabled Asia to consolidate its export capacity, which accounted for 70 percent of the world's rice export, of which 40 percent were shipped to other continents, particularly Africa, contributing to the food security of the world.

Challenges in rice sector development

Despite those significant achievements in rice production in Asia achieved during the last 10 years, a number of challenges and uncertainties have emerged to induce unfavorable conditions for rice production in the years to come. Major challenges and constraints are discussed in the next section.

Shadow of hunger and poverty

The overall constraint is the high incidence of hunger and poverty in the region, as data showed that over 600 million people in Asia and the Pacific are still poor and around 550 million people are hungry and undernourished, accounting for nearly two-third of world's hungry people (FAO 2012, UN 2013). Consequently, the poor rice farmers lack the capital capacity to have access to inputs and new technologies for sustainable rice intensification.

Shrinkage of production resources

Rice production at all times requires land, water, and labor. Nevertheless, the shrinkage of these essential resources is taking place at an alarming rate, and it will aggravate further in the future. Rice land, including the most fertile one, has been shrinking because of the expansion of urbanization and industrialization and also the need of agricultural diversification for higher economic values or better food nutrition. Water resources for rice production have been increasingly competed by the growth of other sectors and by adverse effects of climate change. Because of economic transformation, rice-farming labor has been transferred to urban or non-agricultural sectors, while mechanization application could not keep pace with labor withdrawal out of agriculture. Besides, most rice farmers become aged, and young people are not attracted towards it.

Increase of population and food demand

The population in Asia is projected to grow from the present level of 4.3 billion to 4.9 billion in 2030 at an average growth rate of 1 percent per year. Although rice consumption per capita in Asia tended to reduce because of diet diversification brought in by economic growth, rice consumption is projected to significantly increase in the future in Africa. In fact, the average rice consumption per capita globally during recent decades has been stagnant at about 65 kg per year. It is projected by FAO and IRRI that the global rice consumption will be around 535 million tons by 2030, equivalent to an increase of approximately 1 percent per year relative to the total consumption of 439 million tons in 2010 (FAORAP 2014). Besides the demand of rice with high quality, nutrition and hygienic safety will increase as consumers obtain higher incomes.

Reduction in rice productivity growth

Rice production growth in the past depended on the growth of both productivity and sown area. It is recorded that the productivity growth has declined in recent decades to around 1 percent per year as compared with more than 2 percent per year in the early periods of the green revolution. The primary reasons were attributable to the yield in the irrigated areas approaching a plateau while technology innovations have not made significant breakthroughs in lifting the yield potential as well as improving the yield in rainfed ecosystems. In addition, the pace to close the yield gaps was stalling in all rice-growing ecosystems.

Environmental degradation

The long-lasting negative effects of rice production on environments have been caused by the mismanagement of agronomic practices, particularly the overuse or misuse of agrochemicals predominated by chemical pesticides and fertilizers, and the overexploitation of water resources, particularly groundwater. These improper crop management practices have resulted in various types of environmental degradation, including pollution on ecosystems, water resource depletion, soil quality deterioration, ecological imbalance, soil erosion and severe pest outbreaks, and so on. Such negative consequences could lead to serious setbacks in long-term sustainability and also in food security and human health.

Climate change

The impacts of climate change on rice production have been observed in recent years with frequent occurrences of erratic and extreme events like typhoons, floods, and drought. In the future, the adverse effects of global warming on rice production and productivity will be further aggravated by sea level rise, causing salinity submergence in low-lying coastal rice deltas and nocturnal temperature increase, causing the yield to decline due to adverse effects on rice fertility. Nevertheless, rice cultivation itself contributes to climate change by emitting a large amount of greenhouse gases such as methane and nitrous oxide from paddy fields. It will require arduous efforts to enhance adaptation and mitigation of rice farming to climate change.

Trade constraints

Rice is a sensitive commodity in trade because each country based on its own interests has followed different directions and policies relating to food security, self-sufficiency, protection of domestic market and rice farmers, price subsidies, and so on. The volume of world rice trade has been limited and stagnant at 7 percent of the total global rice production. Therefore, the proposition of restricted rice trade as seen in the 2008 crisis or the lack of market mechanisms would affect adversely rice export and increase price volatility.

Opportunities for rice sector development

Increasing global efforts to eliminate hunger and poverty

Hunger and poverty reduction is still at the forefront of the world development agenda. It is expected that the world will have strong commitments to eliminate hunger and poverty in the post-2015 MDG agendas. Most recently, the UN spearheaded an ambitious initiative, the Zero Hunger Challenge, to totally eliminate hunger in our lifetime. Several countries in Asia already started the implementation of the Zero Hunger Challenge. Because all the targets in the Zero Hunger Challenge rely on agricultural development and the rice sector is an important part contributing to these achievements, the implementation of this challenge would open up enormous opportunities to overcome the bottlenecks in rice production faced in the past.

Fast progress in technology innovations

The fast development in biotechnology and information and communication technology (ICT) would become a driver for technology innovations in agriculture crops, particularly rice. Discoveries in the study of the rice genome are being obtained at a speedy pace to enable the identification of novel genes for improvement of the rice genotypes to adapt to the various demands in production from superior yield to resistance to diseases and pests and adverse environments. Results of scientific innovations have dramatically transformed the farmers' production practices such as the development of new submergence tolerant rice varieties led by IRRI, which were adopted on a large scale by millions of farmers. Likewise, the growing application of ICT will support innovations in crop management, dissemination of scientific and market information, and revolution of the traditional methods in agricultural extension.

Efforts in coping with climate change

Concerted efforts and commitments at global and country levels have been focused to work out initiatives to efficiently cope with the impacts of climate change on agriculture. Among the inspiring initiatives, climate-smart agriculture initiated by FAO aiming at improving productivity, building resilience, and reducing and removing greenhouse emissions has provided a realistic approach to cope with climate change. Hence, the application of climate-smart practices will improve adaptation and mitigation of rice production to climate change.

Trends of the rice sector transformation

The fast economic growth in Asia has driven the transformation of the rice sector in many rice-growing countries to gain sustainable production, competitiveness, and profitability for both rice farmers and consumers. Certain changes have taken place such as the promotion of machinery application, postharvest management practice improvement, farmers' organizations, land consolidation, value chain strengthening and public-private partnership (PPP), and so on. The role of the private sector has been growing both in investment and R&D for rice development.

The vision for the rice sector

In response to the request of countries in Asia and the Pacific for a regional strategy, FAO Regional Office for Asia and the Pacific, in collaboration with member countries, has developed "A Regional Rice Strategy for Sustainable Food Security in Asia and the Pacific," which was endorsed in March 2014.

The vision of the regional rice strategy is for *food security, better-nourished and prosperous rice producers and consumers in the Asia/Pacific region who benefit equitably from a vibrant, innovative, and transformed rice sector that is more productive, efficient, and environmentally sustainable by 2030*. The vision is reflected in six strategic objectives (SOs): (*a*) sustainably increase productivity and nutritive value of rice; (*b*) enhance the rice value chain by improving food quality, diversity, nutritive value, and food safety while reducing the postharvest losses; (*c*) improve mitigation/adaptation of rice farming to climate change; (*d*) reduce the environmental footprint of rice production and enhance the ecosystems functions of rice landscapes; (*e*) improve the efficiency, reliability, and fairness of domestic and international rice markets; and (*f*) enhance the well-being and livelihoods of smallholders, women, and new generation of rice producers.

As expected, the regional rice strategy will provide guidelines and options to support member countries to formulate or reorient their own rice strategy.

STATUS OF HYBRID RICE DEVELOPMENT IN ASIA

Progress in hybrid rice development

Conventionally, a rice variety can be reproduced by using its seeds that originated from self-pollination. This allows farmers to grow their own saved seeds of a variety from season to season. On the contrary, a rice hybrid is produced from the first generation (F_1) hybrid seeds derived from crossing between two genetically-distinct and diverse parents. The advantage of a rice hybrid is attributed to the expression of heterosis or hybrid vigor that makes it superior to its parents and other inbred varieties in terms of yield and other traits, including tolerance to certain adverse growing conditions (cold, temporary drought, acidic soils). Unlike inbred varieties, seeds harvested from a hybrid cannot be used for planting in the next season because the plants' traits in the F_2 generation will segregate, creating variability and causing yield loss and deterioration in the quality of the produce. Therefore, hybrid rice seeds like any hybrid seeds can be used only once for one cropping season.

Hybrid rice in China

The phenomenon of heterosis in rice was neglected for a long time in the past because the rice plant is strictly self-pollinated, small seeded with a single seed per flower. So, it was thought that there was no way to exploit heterosis for practical use. Until 1964, China was the first country to start working on hybrid rice, and it took 10 years to complete the three-line hybrid rice system consisting of a cytoplasmic male sterile line (A line), a fertility restorer line (R line) and a maintainer (B line) to facilitate the production of a hybrid. In 1976, the first hybrid variety was planted in the farmers' fields, etching a landmark of the rice revolution in China. Subsequently, the release of improved new rice hybrids every year accelerated a speedy increase in the planting area of hybrid rice in China, reaching to a peak in 1991 with 17.6 million ha or 60 percent of the total rice area. At present, the hybrid rice area has stayed at about 15.5 million ha, occupying 51.7 percent of the total rice area. The contribution of hybrid rice cultivation to the Chinese rice economy was phenomenal during 1976–2011; the aggregated hybrid rice area mounted 480 million hectares producing an additional 550 million tons of paddy because of the yield increase of rice hybrids on the average by 20 percent over inbred varieties. As a result, the increase of rice production due to hybrid rice adoption supported the feeding of an extra of 60 million people every year and converting 5 million hectares of rice lands for farming diversification or industrial development.

To obtain these achievements, Chinese scientists under the inclusive support of the government have continuously created innovations in hybrid rice technology. The invention of photoperiod- (PGMS) or thermo-sensitive genic male sterile (TGMS) lines that became sterile or fertile depending on day length or temperature led to the successful development of two-line rice hybrids in 1994, which could produce higher yield than three-line ones. It also simplified hybrid seed production and made the hybrid seed cheaper. Consequently, the area planted to two-line hybrids expanded to more than 20 percent of the total hybrid rice area in China.

From 1996, China launched a super hybrid rice program to further raise the magnitude of heterosis by exploiting interspecific hybrid combinations and two-line breeding system. As a result, a yield level of 13–14 tons per hectare was achieved in 2011 in two super rice hybrids. Recently, Professor Yuan Longping, the father of hybrid rice in China, set a target of 15 tons per hectare by changing the morphological characteristics of a hybrid rice plant to have a more favorable yielding structure which combines the advantages of a higher biomass coupled with a higher harvest index for superior yield.

Along with the achievements in hybrid rice breeding, China also made a phenomenal stride in hybrid rice seed production yield, which has reached 3 tons per hectare on the national average by refining hybrid seed production technologies.

Hybrid rice in other countries

A few years after the adoption of hybrid rice in China, the International Rice Research Institute (IRRI) started its hybrid rice research program in 1979 aiming to develop hybrid rice for the tropics, and several Asian countries also initiated their own hybrid rice research programs in the 1980s or early 1990s in cooperation with IRRI and China. In addition, FAO also extended its support to hybrid rice dissemination in Asia through consultancy meetings, capacity building and technical assistance. As a result, several countries outside China could produce hybrid rice commercially. Earlier hybrid rice adopters included Vietnam, India, and Bangladesh, which were followed by Indonesia, Pakistan, and the Philippines, and the recent adopter was Myanmar. Other countries in the region like Iran, Republic of Korea, Japan, Sri Lanka, etc., conducted hybrid rice research but have not adopted for commercialization. At present, the total hybrid rice area outside China is 4.5 million hectares, of which India has the largest area of 2.5 million hectares, whereas the hybrid rice area in Vietnam, Indonesia, and Bangladesh is from 0.6–0.7 million hectares, the Philippines and Pakistan each have around 0.2 million hectares, and Myanmar with less than 0.1 million hectares. In brief, the percentage of hybrid rice area to the total rice area in each country is still marginal, ranging from below 1 percent to 7 percent. Outside Asia, it is known that hybrid rice is grown commercially in the United States on about 0.4 million hectares and in Latin America with less than 0.1 million hectares.

The capacity of domestic hybrid seed production varies among the countries. India and Bangladesh produce sufficient hybrid seeds to meet the current demand, whereas other countries have to rely on seed imports from 50 percent to 100 percent of seed demand. The hybrid seed yield in countries outside China is rather low normally at 1.5-2.0 tons per hectare. In recent years, a number of new rice hybrids developed by national institutes were licensed to private companies facilitating the production of hybrid seeds locally on a relatively wider scale.

It was recorded that the adoption of hybrid rice could increase yield by 15-20 percent on the average equivalent to production increase of 1.0-1.5 tons per hectare in all the countries growing hybrid rice outside China.

Recent trends of hybrid rice development in some countries

There emerged positive trends recently in hybrid rice development in some countries outside China. For example, in India the hybrid rice area expanded speedily in recent years and is expected to continue increase in the future thanks to government's (both central and state) strong policy support and technology advances, or in Myanmar, the government has shown a strong commitment to hybrid rice development and facilitated international investments in hybrid rice industry; and in Bangladesh domestic hybride rice seed production has gained a drastic leap to almost achieve self-sufficiency in hybrid rice seed supply.

Constraints and gaps in hybrid rice development

Two negative trends in hybrid rice development should be considered seriously. The first reflected the low pace of adoption of hybrid rice technology outside China and the stagnancy or decrease of the hybrid rice area in countries growing hybrid rice, whereas it is unlikely to have new adopters ready to apply hybrid rice technology on a large scale in the near future. The second negative trend revealed the marginal increase of the average yield of rice hybrids over 20 years since 1995 to date in China and other countries. A series of constraints in hybrid rice development discussed below are believed to cause these negative trends.

Technology constraints

Rice hybrids

The rice hybrids grown in Asia have been developed from limited sources of male sterility, of which the cytoplasmic male sterile (CMS) of "wild abortive" (WA) type predominated as about 90 percent of the hybrids were developed from this source. Consequently, the narrow genetic base of male sterile sources made the hybrids more vulnerable to pests. Additionally, the magnitude of heterosis in the tropical hybrids was usually lower than that of the temperate hybrids grown in China. In addition, the application of two-line hybrids in the tropics has been rarely studied because of lack of genetic resources and doubt of unsuitable climate conditions for two-line hybrid seed production. Meanwhile, the significant progress in the improvement of inbred rice varieties for the tropics in recent years has posed a difficult choice for farmers to switch to rice hybrids.

It should be noticed that the yield potential of the existing hybrids almost approached a plateau, and in certain cases, hybrids showed a low or inconsistent yield advantage that discouraged the adoption. Case by case, hybrids lacked one or a few desirable traits required by local conditions, for example, grain quality or resistance to particular diseases or pests. Furthermore, lack of *japonica* hybrids or hybrids for rainfed ecosystems slowed down the pace of hybrid rice adoption.

Hybrid rice seed production

With the exception of China, hybrid seed yields are low in other countries because of (*a*) low outcrossing rate of male sterile lines; (*b*) inappropriate management of hybrid seed production, which are more complex than inbred seed production; (*c*) lack of trained personnel for hybrid seed production; (*d*) poor quality of parental seeds; and (e) high seed cost due to low hybrid seed yield. In addition, climatic fluctuations in rainfall and temperature could adversely lower the outcrossing rate, resulting in low seed yields or even total failure.

Apart from low seed yield, the quality of hybrid seeds defined by genetic purity and germination ability has been a common concern, particularly in the case of seeds produced by contract farmers who generally lack postharvest management facilities, including a drying place or seed dryers and storage.

Other constraints in hybrid seed production include shortage of suitable land and labor. To date, the private sector has limited access to large scale tracts of land at locations suitable for hybrid seed production because the fields are fragmented and owned by different smallholder farmers, and private companies themselves could not solve this problem. Additionally, hybrid seed production is labor intensive, as it requires around 80 additional man-days per hectare. The shortage of rural labor limited the scale of hybrid seed production. Lastly, the production of hybrid rice seeds has frequently faced risks due to uncontrolled factors, which discouraged both seed companies and seed growers to invest in hybrid rice seed production.

All these mentioned constraints resulted in deficient supply of hybrid seeds and high seed cost, hindering the expansion of the hybrid rice area.

Crop management

To fully exploit the yield potential of a given hybrid variety, integrated crop management practices, particularly nutrient and pest managements, should be applied properly suited to the variety grown and local conditions. However, farmers generally applied cultural practices based on their own experience and input availability or general recommendations from extension agencies. Applied research on hybrid rice management practices seemed insufficient to identify and transfer location specific technologies to farmers.

Socioeconomic constraints

As an input and knowledge-intensive technology, hybrid rice requires significant investments in both seeds and complementary inputs, as at least hybrid seeds have to be purchased for every season at higher price compared with seeds of conventional varieties. This discouraged poor farmers to grow hybrid rice. In particular, in the case that paddy price is low and stagnant, while the price of inputs tends to increase; farmers are not receptive to hybrid rice due to thin and shrinking profit margins. Furthermore, because of generally poor grain quality, many hybrids command lower market prices than conventional inbreds, which further reduces the benefits of hybrids. In high-yielding areas, when rice production has been far surplus, farmers have a tendency to select high-quality conventional rice for higher market price.

Policy constraints

It is unarguably acknowledged that adequate public investment for strengthening human resources and infrastructure for hybrid rice R&D has been a critical constraint in hybrid rice development. Even in countries where rice research capability has been much developed, the percentage of researchers specialized in hybrid rice to the total rice researchers has been extremely low. Furthermore, insufficient public investment to develop and upgrade production infrastructure has hindered hybrid rice adoption, while the policies of input subsidy practiced by certain countries to encourage farmers to grow hybrid rice have not resulted in sustainable results.

Controversies over the adoption of hybrid rice

Criticisms of hybrid rice have been raised by a few NGOs, focusing on following points (i) hybrid rice technology is not appropriate to the smallholder farmers because they have to purchase hybrid seeds for every cropping season at high price plus other agrochemicals required for hybrid rice cultivation; (ii) the cost of hybrid rice seed is significantly high as compared to inbred rice seeds (3–10 times higher across the countries), and the poor farmers are unable to invest such high cost with risk of economic losses if failed. Indeed, this would be one of the major reasons which prevent the expansion of hybrid rice in many countries, except China; (iii) the hybrid rice seed industry could be monopolized by a relatively small number of large multinational seed companies which control seed supply and impose high seed price; and (iv) the expansion in adoption of genetically uniform rice hybrids and the increased use of agrochemicals accompanied with cultivation of rice hybrids reduce the overall biodiversity, potentially resulting in greater susceptibility to pests and disease. In summary, the critics argued that hybrid rice only brought in super profits to the companies while farmers' sovereignty and livelihood were deteriorated. However, the hybrid rice proponents assumed that hybrid rice is only a part of the rice production system of which the inbred varieties still predominate, thus it is not compulsory for farmers to purchase hybrid rice seeds at any price while the seeds of inbred varieties were available. On the issue of biodiversity reduction, the proponents pointed that it was impossible to solely rely on traditional rice varieties to produce sufficient rice for feeding the ever growing population, therefore the adoption of high-yielding varieties (inbred) or hybrids was indispensable, and in order to minimize the impacts of these varieties/hybrids on biodiversity, inclusive measures for sustainable intensification of rice production could be practiced, including the development of diverse varieties/hybrids.

Future opportunities for hybrid rice development

Increase of rice demand

Rice-growing countries have been looking for improving rice productivity either to lessen the dependence on rice imports and approach to self-sufficiency or to enhance and consolidation of rice exports. In addition, enhancement of rice productivity also facilitates agricultural diversification and economic transformation. All these conditions would be a drive for hybrid rice adoption and make hybrid rice technology attractive for rice-growing countries in the years to come.

Innovations in hybrid rice technology

Advancements in molecular biology, genomics, and biotechnology have resulted in significant improvement in hybrid rice breeding. As a result, new CMS sources different from the predominant CMS-WA source have been identified and applied in hybrid rice breeding to develop rice hybrids derived from a diverse parental background avoiding vulnerability to pests and adverse environments. Complementarily, the routine application of marker-assisted selection (MAS) promises to more efficiently introgress beneficial traits into rice hybrids. For example, several new hybrids possessing better grain quality and resistance to pests have now been released for production. Furthermore, super rice hybrids through inter-subspecific (*indica/japonica*) combinations have been developed successfully in China recently to mark a turning point in raising the rice yield potential. Ongoing research on breeding hybrids for rainfed conditions or aromatic hybrids would bring in new opportunities to expand the hybrid rice area. Efforts for long-term frontier research to develop C4 rice undertaken by international institutes will be transferred into the hybrid rice development in the future.

Besides varietal improvement, the technologies for hybrid rice seed production have been refined and improved in recent years. A national seed yield of 3 tons per hectare has been obtained in China, and a similar yield level has been harvested in demonstrations in other countries indicating the feasibility to improve hybrid seed yield in the future. The use of two-line hybrids could make seed production more efficient. Further, a positive trend is emerging in hybrid rice-growing countries where several seed companies are investing significantly in hybrid rice R&D and seed production and marketing to cope with increasing demand of hybrid rice seed by farmers. The improvement of hybrid rice seed yield coupled with the increase of hybrid rice seed production to reduce seed cost will be a great booster to adoption of hybrid rice on a large scale.

Policy and institutional innovations

In recent years, there has been an increasing trend in investments by the private sector for R&D of hybrid rice, and at the same time, governments and public institutions have started various modalities of partnership with the private sector. As a result, a number of new rice hybrids were developed by private companies and commercialized successfully. Besides, companies have been licensed rice hybrids bred by public institutes for commercialization. There were also positive institutional changes to enhance the efficiency of public sector management and attract more investment from the private sector. The emergence of a strong PPP has provided a prospect to expand the scale of hybrid rice adoption.

STRATEGY OF SUSTAINABLE HYBRID RICE DEVELOPMENT IN ASIA

Vision for hybrid rice development

In view of the progress, challenges, and opportunities in hybrid rice development in Asia and under the direction of the regional rice strategy, the vision of sustainable hybrid rice development in Asia towards 2030 is that of *substantial and sustained increase of rice productivity in both irrigated and rainfed ecosystems contributing to food security, poverty reduction, and hunger elimination, and shared benefits amongst rice farmers - particularly smallholders - consumers, and the business sector in the region.*

The advantage of hybrid rice is its capability to have a higher yield potential than conventional varieties under the same production conditions. In view of the stagnancy in rice productivity so far, it has been believed that hybrid rice will hold a more focal position in rice production systems than in the past. Hybrid rice should be developed for both the irrigated and the rainfed ecosystems, as the yield of existing conventional varieties in rainfed ecosystems is rather low. It is obvious that the increase of rice productivity will be a key factor of production increase contributing to food security, hunger, and poverty elimination. The increase of rice productivity must be sustainable by the application of optimal and environment-friendly practices to save resources and inputs and protect environments. At the end, hybrid rice should bring in equitable benefits to all the stakeholders involved in its development, including farmers, seed growers, rice consumers, and the business sector.

To turn the vision to reality, SOs and key themes and options are proposed, as follows.

Strategic objectives

The following four key SOs are proposed to achieve results from the vision and the future opportunities of hybrid rice discussed in the above sections.

SO1: To obtain higher productivity from hybrid rice with accepted grain quality

First and foremost, rice hybrids should perform better than conventional varieties grown under the same agroecological and management conditions. In addition, the combination of high yield and quality was a constraint of rice hybrids in the past. Therefore, to make hybrid rice accepted, improvements in grain quality should become an additional objective in parallel with high yield in hybrid rice development.

SO2: Adoption of hybrid rice on a large scale in various ecosystems by a large number of farmers

The impact of hybrid rice would be more noteworthy if its application scale can be expanded to a large number of farmers in various ecosystems; therefore, scaling of hybrid adoption should be a key objective in hybrid rice development in the future. To meet this requirement, different rice hybrids suited to a wide range of ecosystems and production systems should be developed and made available. In addition, the hybrid rice seed production should be efficient to make hybrid seed available at affordable prices so that many farmers can have an access to it.

SO3: Promotion of the private sector in hybrid rice development

As the main producer and supplier of hybrid seeds, the private sector plays a key and significant role in hybrid rice development. In addition, the private sector is also involved in R&D, particularly applied research and technology transfer to farmers. Therefore, one of the goals of a strategy for hybrid rice development must aim at encouraging the involvement of the private sector through seemly policies and the effectual PPP.

SO4: Enhancement of benefits to rural community and smallholder farmers

Apart from the impact on food security, hybrid rice should also bring in socioeconomic benefits to rural communities and smallholder farmers. This states an essential aspect of sustainable hybrid rice development in the future, which requires innovative approaches to strengthen capability at the community level and to make hybrid rice receptive to small and resource-poor farmers.

Key themes and options

To translate the above SOs into activities and programs, the following key themes and options are discussed in the present section:

(a) Improvement of rice hybrids adapted to various ecosystems and climatic change
(b) Improvement of hybrid rice seed production and supply
(c) Optimization of crop management practices for sustainable hybrid rice production
(d) Support of smallholder farmer for hybrid rice adoption
(e) Strengthening extension and technology transfer for hybrid rice adpotion
(f) Facilitating the establishment of mutually-beneficial public-private partnership
(g) National coordination mechanisms and international cooperation on hybrid rice development
(h) Policy options for hybrid rice technology innovations and commercial adoption

Improvement of rice hybrids adapted to various ecosystems and climatic change

Breeding approaches

(a) Broadening genetic diversity of male sterile sources and parents

Most cytoplasmic male sterile lines used to develop rice hybrids so far have the same cytoplasm source, namely “wild abortive” (WA). Consequently, this status of the narrow genetic diversity of CMS sources has resulted genetic uniformity, limited heterosis magnitude and vulnerability to pests of hybrids as experienced in the past. Therefore, it is worthy to exploit and search for different new CMS sources adapted to tropical environments to broaden genetic diversity of parental genotypes. In addition, to accelerate the application of two-line rice hybrids, research on new TGMS sources suitable to the tropic should be given invigorated efforts. Experiences have shown that TGMS sources must possess stable temperature threshold to avoid risks in hybrid seed production due to temperature fluctuation. The performance of rice hybrids is determined by the traits of their parental male sterile lines; therefore research efforts should be focused on development of desirable male sterile lines. Generally, the most important attributes of the male sterile lines affecting the performance of the resulting hybrids include high and stable heterosis, high general combining ability, high outcrossing potential, good grain and cooking quality, and resistance to diseases and pests.

(b) Exploitation of inter-subspecific hybrids

Evidences have shown that the rice hybrids derived from inter-subspecific combinations (*indica* x *japonica*, *indica* x *javanica*) have given rise to the higher heterosis magnitude than those from the intra-subspecific combinations (*indica* x *indica*, *japonica* x *japonica*). However, the problems faced in developing inter-subspecific hybrids include the limited choice of parents due to the low seed setting and other negative effects of inter-subspecific hybrids. To overcome the low fertility of inter-subspecific hybrid, wide-compatibility (WC) genes could be transferred to parental lines to improve the seed setting.

(c) Improvement of two-line hybrid rice breeding

The two-line breeding system based on TGMS lines or PGMS without maintainer lines helps broaden the choice of parents and simplify hybrid seed production procedures as the production of male sterile lines by crossing with maintainer lines is not needed any longer. Because of marginal differences of day length in the tropics, PGMS lines are less applicable, whereas TGMS lines have been found to have high potential as the temperature in the tropics varies widely. In addition to this advantage, two-line TGMS hybrids normally had higher yields than three-line hybrids because of potential wide genetic diversity. However, the TGMS systems could be impacted by temperature increase due to climate change. Therefore, inclusive research on two-line breeding based on TGMS should be given priority in the years to come.

(d) Exploitation of novel tools in hybrid rice breeding

Marker assisted selection (MAS) has become an efficient tool to support hybrid rice breeding by detecting and transferring genes for fertility restoration (Rf), thermo-sensitive male sterility (tms) or WC, and genes for tolerance to biotic or abiotic stresses into the parental lines. Likewise, quantitative trait loci (QTL) or heterotic groups for high yield potential can also be detected and mapped for introgression into parental lines. Furthermore, with advances in genomic research, novel beneficial alleles are discovered from untapped rice germplasm and exploited for developing new hybrids. The ongoing frontier research for a long-term goal of scientific breakthroughs in developing C4 rice should be given adequate investment to sustain international research efforts.

Development of rice hybrids adapted to various ecosystems and local conditions

The rice ecosystems are widely diverse across the region and within each rice-growing country. To make hybrid rice widely adopted, it is essential to have varieties that could meet the production conditions and market demand in the target areas. Different ecosystems and production conditions or market preferences would require different rice hybrids to provide the best adaptability and performance. However, common desirable traits in a hybrid variety are high heterosis, potential for high hybrid seed yield, and preferred grain quality as well as resistance to major diseases and pests.

Grain quality has a strong influence on the farmers' decision to select a variety to grow regardless of whether it is a hybrid or a conventional variety. The failure of certain hybrids because of their inferior grain quality in the past has been a worthy experience. The increasing trend of consumption of high-quality rice as a consequence of economic growth in the region has redirected breeding objectives of hybrid rice. Attributes of grain quality vary depending on consumers' preferences and market demand, including the international market if rice is exported. Aromatic rice is attractive in the high-income market and for export; therefore, the breeding of aromatic rice hybrids is highly rewarding. Other grain quality attributes should also be considered, including head rice yield, amylose content (low or high) and grain appearance (long or bold grain, whiteness, and translucence).

The breeding of rice hybrids should be aimed not only for irrigated ecosystems but also for rainfed ecosystems, particularly the favorable rainfed lowland ecosystem where its present productivity can be raised further by using rice hybrids. Resistance to diseases and pests that are prevalent in the target areas such as brown planthopper, white-backed planthopper, bacterial leaf blight, sheath blight, or blast should be a prerequisite in hybrid rice breeding. In addition, rice hybrids are required to possess tolerance to abiotic stresses depending on the growing conditions (drought, submergence, salinity, cold, or heat) to adapt to unfavorable ecosystems or climate change. Recently, a notable success was witnessed in the development and adoption of inbred mega-varieties that are tolerant to submergence, and efforts are also underway for breeding inbred varieties tolerant to drought, salinity, or even multiple abiotic stresses. Similar approaches should be applied in the development of new rice hybrids. Breeding rice hybrids for higher input use efficiency (nutrients, water, etc.) deserves to be focused on, to make the varieties responding suitably to "Save and Grow" principles and mitigation practices such as alternate wetting and drying (AWD) irrigation and direct seeding.

Lastly, rice hybrids should possess the suitable growth duration. In some places, early maturing varieties with a duration of 90 - 110 days are required to escape flood, drought, or salinity, on the other hand, there is a need of long-duration hybrids for certain unfavorable ecosystems.

Rice hybrids testing, release, and transfer to production

Before approval for releasing new rice hybrids developed in the country or imported into commercial production, the varieties should be tested extensively under a well-organized national testing network as practiced in some countries. The multidisciplinary testing includes multi-location yield trials over seasons/years in target ecosystems with appropriate check varieties, pest and disease evaluation, grain quality analysis, etc. The operation of the national testing network should be done and funded by public agencies to ensure neutrality in testing.

After releasing, it requires a strong extension program with well-trained personnel to transfer newly released rice hybrids to farmers through demonstrations on the farmers' field, training, and mass media campaigns, and so on, to train a large number of farmers on hybrid rice growing efficiently. Private companies or breeding institutes should also have policies in place to transfer newly released varieties to farmers in partnership with public extension agencies.

Improvement of hybrid rice seed production and supply

Farmers growing inbred varieties can use saved seeds from their fields in the previous season. But for rice hybrids, they have to purchase hybrid seeds every cropping season. Therefore, the availability of hybrid seeds at affordable price to farmers is the most important determinant to expand the planting area of hybrid rice. Since rice is a strictly self-pollinated crop, small seeded, and each pollination producing one seed, the production of hybrid seeds is difficult as compared with open-pollinated crops such as maize, resulting in an insufficient supply of hybrid seeds produced domestically in most hybrid-rice-growing countries. To overcome the seed shortage, countries had to depend on seed imports to satisfy the demand to some extents, but they faced other constraints such as transportation cost, quarantine control, adaptation of the varieties, technology transfer issues, high seed cost, unsustainable production and so on. Therefore, strengthening the capacity of domestic seed production or the seed industry in general is an optional strategy to make hybrid rice more popular in the future. Ensuring a strong system of domestic hybrid seed production and supply requires (*a*) the active involvement of the private sector; (*b*) technology innovations to increase hybrid seed yield and quality; (*c*) seed certification and quality control; (*d*) marketing and trade promotion of hybrid seeds; and (*e*) fair national seed regulations or rules for the seed industry.

Involvement of the private sector

Although the public seed agencies could produce parental seeds and limited amount of hybrid seeds, commercial seed production and supply have been mainly undertaken by the private sector. Therefore, governments should provide favorable environments and incentives to attract the private sector to invest in hybrid seed industry and advocate PPP in capability building. Examples of support given by governments to the private sector to promote hybrid seed production can be listed as (*a*) supply of of parental lines of new hybrids developed by public institutions to produce seeds based on mutually agreed MoU (*b*) facilitation of long-term land allotment for seed production, (*c*) infrastructure investment for specialized seed production zones, (*d*) organization of farmers to facilitate community-based hybrid seed production, (*e*) establishment of an insurance scheme for seed growers, (*f*) tax reduction for seed business, and so on.

Increase of hybrid seed yield and quality

Optimizing seed production technologies could significantly increase the present level of hybrid seed yield. Therefore, research on development of innovative hybrid seed production technologies at national and international institutes should be intensified to achieve a target of hybrid seed yield. Research objectives would cover the selection of hybrids with their parents possessing high outcrossing capability, identification of suitable locations/growing seasons, genetic purity of parental seeds and crop management practices in which flowering synchronization of parental lines is critical. In addition, infrastructure bases (irrigation facilities, roads, electricity, etc.) in the seed production zones should be invested adequately by the government to attract the private sector to participate in hybrid seed production. Experiences show that the establishment of specialized zones for hybrid rice seed production has been a good option to develop an efficient seed industry. In addition, in hybrid rice seed production, postharvest management infrastructure for seed drying, processing, storage, and packaging are critically needed to ensure the quality of seeds supplied to farmers. Hybrid rice seed production requires skillful manpower; therefore, the training of researchers, technicians, and seed growers should be done intensively both by public extension systems and private companies. International institutions such as FAO, IRRI, and APSA could assist national agencies and the private sector to train their staff on hybrid seed production including mechanization and seed postharvest technologies. Lastly, in view of the increased shortage of farm labor, the application of machinery in seed production would be an ideal alternative, so it is worthy to invest in research and development in this field.

Seed certification and quality control

Various aspects should be paid attention to develop a good system of seed certification and quality control in the country, including (*a*) issuance of technical procedures of hybrid rice seed production and standards of seed quality for hybrid seeds and parental seeds, (*b*) upgrading or setting up seed quality control laboratories in public agencies and companies, and (*c*) regular training of personnel of inspection of seed production and quality control in both public and private sectors.

Marketing and trade promotion

Unlike maize farmers, a majority of rice farmers are not familiar with hybrid seeds. Therefore, marketing promotion to help rice farmers be aware of the advantage of hybrid seeds can be carried out through mass media campaigns and particularly farm demonstrations. Free market and trade of hybrid rice seeds should be facilitated, and at the same time, strong measures to encounter the trade of counterfeit or poor-quality hybrid seeds should be done according to legal regulations and mechanisms (seed law, seed act, trademark protection, etc.).

Optimization of crop management practices of hybrid rice production

The productivity of a hybrid variety depends not only on its genetic potential but also on the crop management practices to realize that yield potential. The difference in farmers' skill to manage cultural practices of hybrid rice production appears to be one of the major limiting factors causing wide yield gaps in hybrid rice. To overcome this constraint, R&D for integrated crop management of hybrid rice should be strengthened. The crop management practices should be suited to the rice ecosystems, production systems, and local conditions. Innovative approaches in integrated management practices applied to hybrid rice should be established following the principles and good practices of sustainable crop production intensification as promoted by FAO under the banner of "Save and Grow" and "Climate-Smart Agriculture" focusing on (*a*) reducing the seed rate, particularly for direct seeding cultivation system; (*b*) increasing efficiency in integrated nutrient management (INM); (*c*) enhancing ecological measures in integrated pest management (IPM), making optimal use of the ecosystem services provided by natural biological control; (*d*) applying water-saving technologies; (*d*) mechanization application; and (*e*) ICT application. To suit to various production systems and ecosystems, recommendations of cultural practices should be site-specific and particularly variety-specific to fully exploit the yield potential of rice hybrids. The application of ICT should be promoted to provide effective tools in crop management and information dissemination to farmers.

Support of smallholder farmers for hybrid rice adoption

In order to promote the participation of smallholder farmers in hybrid rice production, it would be important to provide public support at the initial stage of hybrid rice introduction, which may include (i) price subsidy to hybrid rice seeds in a limited period; (ii) provision of credits to support smallholder farmers having access to inputs, particularly hybrid seeds that have to be purchased timely for planting; (iii) training of smallholder farmers in hybrid rice cultivation and hybrid rice seed production; (iv) organization of smallholder farmers in farmers groups to promote community-based hybrid rice seed production programs; (v) promotion of market information systems and expansion of hybrid rice market; (vi) introduction of subsidy (or support) to crop insurance scheme for smallholder farmers who grow hybrid rice or producing hybrid rice seeds, and (vii) investment for improving infrastructure bases at community level to provide favorable conditions for smallholder farmers to optimize production output and profitability.

Strengthening extension and technology transfer for hybrid rice adoption

Effectual extension systems would help accelerate the pace of hybrid rice adoption by farmers and make sure the technology is sustainable at community level and farmers' fields. Although agricultural extension can be commercialized in terms of service supplies, in most developing countries with the majority of farmers as smallholders, public extension system still holds a central role in technology transfer to farmers, particularly in the case of hybrid rice technology that is knowledge intensive and locality specific. In complementation to the public sector, extension activities undertaken by the private sector can support farmers to optimize their production practices appropriate to particular hybrids they grow. Capability building, particularly human resource development is a prerequisite to establish a soundly organized extension system from the central to the regional and community levels for hybrid rice dissemination and adoption, in which the extension activities at community level are fundamental to the sustainability of the technology. In the various extension methods applied to hybrid rice, the approach of Farmer Field School (FFS) appears highly appropriate to induce farmers to be proactive in technology adoption. Women should be empowered through training to actively be involved in hybrid rice cultivation and seed production. Modernization of the value chain of the hybrid rice industry could attract more young farmers to engage in hybrid rice production or seed business.

Facilitating the establishment of mutually-beneficial public-private partnerships

PPP is a backbone in hybrid rice development because of the indispensable linkages of technology generation, diffusion, and commercialization of products. Therefore, an effective partnership would bridge the distinct strengths of public and private sectors to attain the common goal. Experiences showed that in countries with strong PPP, the pace of hybrid rice adoptions has been faster. Public agencies including international research institutes have important roles in scientific research, training, and extension providing a base for the development of the hybrid rice industry, while the private sector predominantly undertakes hybrid seed production and distribution. The outputs of research activities in the public sector like parental lines of new hybrids or innovative seed production technologies should be transferred to private companies for large-scale production of hybrid seeds. Public agencies can also provide germplasm or breeding materials for the private sector to develop new rice hybrids for commercialization, and governments should enable the movement of seed materials within and across countries.

The transfer of hybrid rice technology to farmers requires a strong extension system, which is operated by public and private sectors and NGOs. The public sector can also provide institutional support and legal mechanisms to create favorable environments for the private sector to engage in hybrid rice industry, particularly to invest in long-term production and supply of hybrid rice seeds. The enforcement of IPR such as plant variety protection (PVP) and other international regulations like the International Union for the Protection of New Varieties of Plants (UPOV) by government authorities is a prerequisite to attract investment of the private sector in the hybrid rice industry, particularly to transfer the latest technologies into production. Hence, governments should have transparent IPR policies and enforcement to strictly prevent IPR infringements. PPP in infrastructure investment is also significant to upscale the adoption of hybrid rice. The establishment of specialized seed production zones or postharvest management infrastructure and application of machinery entailed both the investment of public and private sectors.

National coordination mechanisms and international cooperation on hybrid rice development

A national platform for hybrid rice development would provide a mechanism that synergized the activities of various stakeholders engaging in the hybrid rice industry including public and private agencies, NGOs and civil organizations, local communities and farmers.

At the international level, cooperation in R&D of hybrid rice and networking should be maintained and strengthened through international platform for hybrid rice development, such as Hybrid Rice Development Consortium (HDRC) initiated by IRRI, which has been proven as an effective international platform of cooperation for promoting hybrid rice development, particularly in technology transfer and germplasm exchange. International institutions, including FAO, IRRI, APSA, and ISF should come out with position and advisory papers to make policy makers aware of the benefits of clear policies for the exchange of rice germplasm and technology transfer for the food security of countries in Asia. These institutions in cooperation with ASEAN and SAARC would sponsor regional dialogues on harmonization and standardization of technical procedures in hybrid rice development, including variety testing and commercial release, sanitary and phytosanitary measures, and plant quarantine certification for hybrid seeds to streamline the dissemination of hybrid rice technology between countries in Asia.

Besides international cooperation, South-South cooperation under the assistance of FAO would be a suitable mechanism to disseminate hybrid rice between countries in Asia because such kind of cooperation has shown effectiveness in the past and is becoming a rising trend in the future.

Policy options for hybrid rice technology innovations and commercial adoption

The large-scale adoption of hybrid rice requires a simultaneous combination of technology discovery (rice hybrids) and technology commercialization (hybrid seeds). Weakness in either one of these two components or in both the components certainly limits the adoption rate of hybrid rice technology. Therefore, policy options should be focused on improving and enhancing the national strengths in hybrid rice technology innovations and commercialization.

First, increased investment in R&D and E (extension) for hybrid rice should be firmly committed and implemented by the governments to build up national capacity of human resources and infrastructure to enable the development and dissemination of hybrid rice technologies suited to local conditions. A strengthened national capacity could facilitate long-term upstream research to provide innovative technologies for the private sector application and promote international cooperation programs in R&D, including shuttle breeding of hybrid rice to fast-track product development and joint venture in hybrid rice research between the private companies and public institutions.

Second, the governments should provide incentives for the private sector, in particular to improve the capability and efficiency of seed production system and increased hybrid seed supply at affordable cost. To realize this goal, relevant policy options should be adopted to address the following issues: *(a)* transparent, uniform, predictable, and defined policies on germplasm exchange and relating issues to facilitate access to and exchange of rice germplasm between all stakeholders and between countries and to allow the import or export of hybrid rice parental lines and commercial hybrid rice seeds with minimal regulatory regulations to enhance seed production and commercial hybrid rice seed trade in Asia; *(b)* adoption of legal regulations to streamline technological procedures, standards, intellectual property rights (IPR) protection, plant variety protection (PVP), and so on; *(c)* allocation of land for long-term use for seed production; *(d)* organization of smallholder farmers to produce hybrid seeds; *(e)* tax reduction in hybrid rice seed business; and *(f)* proactive formulation and implementation of PPP.

Third, policy options should be focused on improving the conditions at the community level and farmers to become more receptive to hybrid rice technology. Investment should be prioritized for improving infrastructure at the community level, provision of credits, training of farmers and seed growers, technology transfer, crop insurance, and marketing of the product. Subsidy support through seeds, fertilizers, or other inputs should be considered carefully on a case-by-case basis to avoid the distortion of free market and erode the viability of the technology. To adjust policy interventions, the government and independent institutions should undertake periodically a comprehensive and scientific analysis of impact of hybrid rice on productivity growth, food security, farmers' income, consumers' benefits, environment, and climate change.

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