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The prospects for hybrid rice in India

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Abstract The government of India has set a target of expanding the cultivation of hybrid rice to 25 % of the area occupied by the crop by 2015. Current growth trends suggest that this target will not be met, despite the potential contribution of hybrid rice to lagging growth in national rice yields, overall rice production, land-use reallocation and food security. This unfolding experience suggests a different trajectory from that of China, where hybrid rice accounts for more than half of the area under the crop and has contributed significantly to yield and output growth, reallocation of land to other agriculture and non-agricultural uses and food security. This paper examines the technical challenges, market opportunities, and policy constraints relating to hybrid rice in India.

Keywords Hybrid rice · Agricultural research and development · Technological change · Innovation · India

Introduction

Rice productivity growth is critical to improving the livelihoods of households throughout Asia. Higher yields increase on-farm incomes and ensure supplies of rice that reduce or stabilize prices for both urban and rural food-insecure households (see, for example, Lin and Pingali 1994). Hybrid rice provides one important avenue through which these higher yields can be achieved. Moreover, because hybridization provides innovators with the ability to recoup their investments in research, hybrid rice represents a technology platform on which both private-sector scientists and entrepreneurs can make profitable and socially beneficial investments. As such, many policymakers throughout Asia see hybrid rice as a means of reinvigorating stagnant yield growth in rice, boosting rural incomes, and stimulating private investment in rice improvement.

In China, the development and promotion of hybrid rice over the past several decades has led to widespread adoption, with hybrids accounting for more than half of all area under rice cultivation in the country as of 2010. The increase in rice yields attributable to hybrid rice has, in turn, improved food security for an estimated 60 million additional people per year (Li et al. 2010). Elsewhere in Asia, however, hybrid rice cultivation is lagging. Hybrid rice accounts for less than 10 % of the area under rice cultivation in Bangladesh, India, Indonesia, and the Philippines and just 10 % in Vietnam. A range of technical challenges, market failures, and policy constraints has limited the development and diffusion of hybrid rice outside China to date. This paper aims to address these challenges, failures, and constraints and recommend policy solutions to improve the prospects for hybrid rice in South Asia, with a particular emphasis on the Indian context.

A novel way to analyze issues surrounding hybrid rice is to examine the processes behind the product—that is, the factors that are encouraging or inhibiting the discovery, development, and delivery of hybrid rice. This type of analysis requires an integrated framework that opens the "black box" of the research production function. This paper examines the hybrid rice market by focusing on the processes through which new technologies are transformed into economically relevant products. It does so by applying a novel approach to analyzing agricultural science, technology, and innovation policy.

This framework helps to identify (1) the key actors, assets, and processes engaged in the production, exchange, and use

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of new technologies; (2) the actions and interactions that enable these actors to invest in process innovations; and (3) the policies and institutions that influence their actions and interactions. An analysis of the complex systems surrounding hybrid rice (or any other technology) can provide a clear picture of the precise areas in which policy interventions may result in accelerated development and delivery.

This paper proceeds as follows. In Section "Conceptual framework," we present the conceptual framework through which we examine the opportunities and challenges associated with the discovery, development, and delivery of hybrid rice technologies in India. In Section "Data and data sources," we introduce the various data sources used in the qualitative and quantitative analysis throughout this study. Section "Background" presents a historical and contextual background of hybrid rice technologies and patterns of adoption in India. Section "Future scenarios and challenges for hybrid rice" discusses the technical, social, economic, and policy dimensions of hybrid rice in India. Section "Conclusions and policy recommendations" concludes with a set of actionable policy recommendations for further research, development, and delivery of hybrid rice in India.

Conceptual framework

There are obvious challenges in transforming a technology such as hybrid rice into an economically relevant production factor. One way of addressing these challenges is to develop a better understanding of the complexity in how factors of technology production—scientific capital, technical know-how, breeding materials, and seed production systems—are translated into real outputs, such as marketable quantities of hybrid rice seed or hybrid rice as a tradable commodity itself.

One way of better understanding these issues is to examine the processes that translate science into viable technologies and, ultimately, into commercial products, as well as the incentives that motivate individuals, firms, and governments to invest in these processes. This type of examination requires shifting our analytical emphasis to the question of how, rather than why, science, technology, and innovation (ST&I) policies and investments should be made, which requires focusing more on systemic complexity and knowledge gaps rather than on cost–benefit analysis.

The ST&I framework used in the present study answers the "how" question by emphasizing the roles played by diverse actors in the production, exchange, and use of ST&I products and processes; the institutions and incentives that condition these actors' actions and interactions; and the precise policy interventions that are most likely to result in welfare-improving outcomes. It does so by focusing on the analysis of optimal investment, collaboration, and risk management strategies that define the critical decisionmaking points for investment in agricultural ST&I.

The framework examines decision points at three stages of the innovation process—discovery, development, and delivery (Fig. 1). During this process, knowledge, scientific, human, and productive capital are all transformed into marketable outputs and measureable inputs through an iterative process of discovery, development, and delivery. *Discovery* describes the investment, collaboration, and risk management strategies related to scientific and technical inquiry at the earliest phase of innovation. *Development* describes the translation of science into technology and the market opportunities, regulatory hurdles, and other constraints associated with this process. *Delivery* refers to the adoption and uptake of a technology through various market and nonmarket distribution channels that are influenced by the economic behavior of individuals, firms, and governments.

At the nexus of discovery, development, and delivery is a series of institutional and industrial strategies involving investments, collaborations, and risk management. This framework illustrates the discovery, development, and delivery process as an iterative process of learning that results in innovative technologies (e.g., interactions between discovery and delivery facilitates demand-driven innovations), innovative processes (e.g., interactions between discovery and development facilitate new methods and approaches for streamlining the research and development pipeline), and innovative dissemination (e.g., interactions between development and delivery facilitate new methods for transmitting information about the technologies or for transmitting the technologies themselves).

Table 1 summarizes these three stages, highlighting the clearly defined investment, collaboration, and risk management strategies that innovators and policymakers must address when making critical decisions and pursuing specific actions. Where information and analysis are limited and where public policies give little guidance in steering decisions and actions to optimal outcomes, innovators face greater levels of uncertainty. This uncertainty necessarily reduces the probabilities that a given technological opportunity will enhance productivity, reduce poverty, or promote equity in developing-country agriculture. Efforts to bridge this information gap and design farsighted public policies are an essential contribution of any analytical work on ST&I.

These differentiated stages of discovery, development, and delivery are based on overlaps and interactions, a reality that draws attention to the fact that most innovative opportunities cannot be exploited simply on the basis of a linear process that moves from upstream science into downstream application. Instead, the process begins with a widely defined set of assets: explicit inputs, such as known stocks of scientific capital,

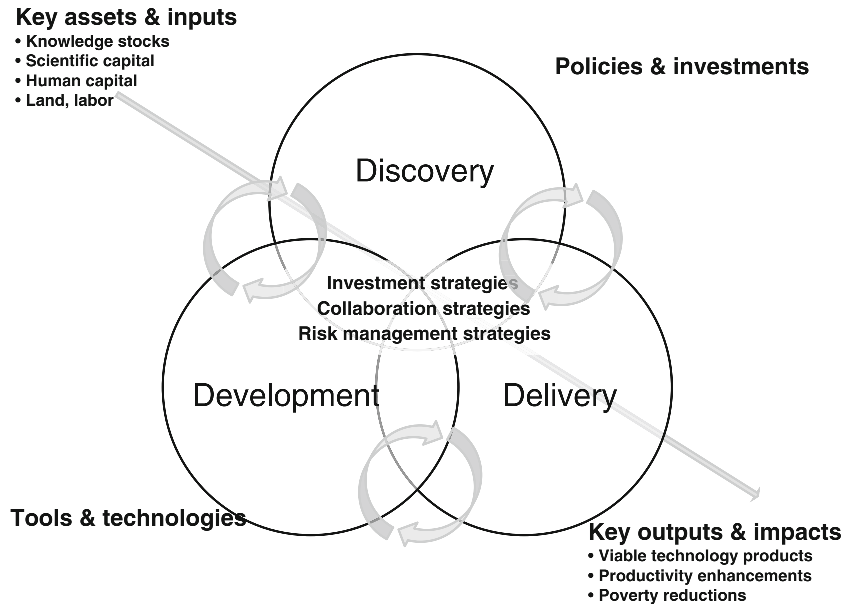


Fig. 1 From discovery to delivery: The ST&I framework. Source: Authors' creation

other forms of capital, land, and labor, as well as more implicit or tacit inputs, such as scientific experience, indigenous knowledge, and managerial capacity. The application of these assets to a particular problem or production constraint leads to a nonlinear progression influenced by (1) the availability of appropriate tools and technologies (the "state of the art"); (2) the capacity of agents to iterate, learn, and innovate through this progression ("innovative capabilities"); and (3) the existence of appropriate policies and investments in support of ST&I (the "enabling environment"). In short, although ST&I can contribute to solving problems in developing-country agriculture, the solutions require more than just good science. They also require the right tools and technologies *plus* the right policies and investments.

Data and data sources

This paper relies mainly on publicly available data on rice research, cultivation, and production garnered from government and private-sector sources. Data and analysis were extracted from a range of sources, including peer-reviewed journal articles, government statistical reports, private data-

Table 1 Key stages and strategies in an ST&I framework

Key stages	Product discovery	Product development	Product delivery
Key function	Basic research and upstream science	Applied/adaptive research and product introduction	Product marketing and distribution
Investment strategy	Identify or acquire relevant research assets; Identify research (technical) strategy	Transform research into a commercial product; Develop production systems and business models for commercialization	Develop marketing strategies and distribution systems
Collaboration strategy	Identify and leverage research networks and partnerships; Review intellectual property (IP) rights needs to identify licensing or collaboration priorities	Identify and leverage product development networks and partnerships	Manage in-house versus outsourced production; Identify marketing partners and partnering strategies
Risk management strategy	Identify regulatory issues associated with the research	Identify market risk issues associated with the product; Collect and manage environmental safety, human safety, and other regulatory data	Manage production and product safety; Manage market risk; Identify industry structure and concentration issues; Ensure IP protection and product stewardship

Authors' creation

bases, and documents from industry sources. Key sources are as follows.

Key informant interviews

Information was gathered from a series of unstructured interviews held from 2008 to 2010 in several locations across India. Interviews were conducted with people knowledgeable about India's seed and agricultural biotechnology industries, including corporate decision makers, private-sector researchers, public regulators, social science researchers, policy analysts, and biophysical scientists working in both public and private research units. Table 2 provides a breakdown of key informants by sector. Questions covered during the interviews were related to seed and agricultural biotechnology market opportunities in India, research and development (R&D) investment strategies and constraints, product delivery strategies and constraints, intellectual property rights (IPRs), technology forecasts and opportunities, and regulatory issues.

Francis Kanoi Marketing Research Group survey

The Francis Kanoi Marketing Research Group conducted a survey-based study on rice cultivation and the rice seed market during 2008–2009 in India. The survey's main objectives were to estimate the demand potential for rice seed, identify various seed sources and their respective market shares, estimate the costs of cultivation of rice across various states and production zones, and estimate the market share of various companies in the hybrid rice seed market. The survey covered 11,076 rice farmers across 139 districts (districts with more than 30,000 hectares under rice cultivation) in the 16 major rice-growing states of India for the 2008–2009 agricultural season.

Table 2 Key informants interviewed, 2008–2010

Affiliation	Number
Private sector (managers, researchers, others)[a]	36
Public sector (regulators, researchers, others)[b]	35
Donors, nongovernmental organizations, charitable foundations, and others[c]	6
Total	77

Authors' creation

[a] Includes representatives of industry associations

[b] Includes researchers from the Consultative Group on International Agricultural Research

[c] Includes representatives of donor agencies, international organizations, charitable foundations, and nongovernmental organizations

Cereal Systems Initiative for South Asia (CSISA) baseline household survey

The Cereal Systems Initiative for South Asia (CSISA) baseline household survey was conducted by researchers from the International Rice Research Institute (IRRI) and the International Maize and Wheat Improvement Center (CIMMYT) during the second half of 2010 and the first quarter of 2011. The survey sample was generated based on a stratified random sampling approach within the domains of the eight innovation and delivery hubs established as part of the initiative.[1] In all, the survey contains information on 2,627 households. Although limited to the selected districts in Bihar, eastern Uttar Pradesh, Haryana and Tamil Nadu, and thus not nationally representative, the sampling strategy is such that the samples are intended to be representative of the areas included in the hub domains.

Background

Hybrid vigor, or heterosis, is the increase in yield, uniformity, or vigor of cultivated plants that results from genetic contributions derived from the crossing of distinct parental lines. Its economic value for breeders lies in the fact that yield gains conferred by heterosis decline dramatically after the first generation of seed (F1), thus compelling farmers to purchase new F1 seed each season if they want to continually realize these yield gains. This contrasts with conventional open pollinated varieties (OPVs) or inbred varieties (for rice), in which harvested grains can be stored and used as seeds in the following year.

This unique characteristic has been a driving factor behind investment in crop improvement for maize and several other crops. Annually, maize receives more than US$1 billion in private R&D investment in the United States—more investment than any other crop—owing largely to the incentives that hybridization provides to private breeders (see Fernandez-Cornejo 2004; Fuglie et al. 1996).

Hybrid maize cultivation has spread throughout the world, including into developing countries in Latin America, Sub-Saharan Africa, and Asia (Morris 1998). Hybrids of other crops, such as sorghum, pearl millet, cotton, and many vegetable crops, have also made similar inroads in developing countries (see, for example, Pray and Nagarajan 2010). Hybrid rice got its start in India in 1954, when heterosis in rice was first documented by S. Sampath and H. K. Mohanty at the Central

[1] The eight innovation and delivery hubs included five in India, two in Bangladesh, and one in the Terai region of Nepal. The data and information presented in this paper are drawn from a sample of districts in which CSISA operates in Bihar, eastern Uttar Pradesh, Haryana, and Tamil Nadu.

Rice Research Institute, Cuttack, in the Indian state of Odisha (see Sampath and Mohanty 1954).

Despite the lucrative benefits of hybridization to both firms and farmers, substantial criticisms and concerns exist over their place in developing-country agriculture. First is the concern that seasonal or annual purchases of hybrid seed are too costly for many resource-poor, small-scale farmers in developing countries (Kuyek et al. 2000). Several points are worth noting regarding this contention. First, much evidence suggests that purchasing seed—both inbred and hybrid—is a fairly common practice among rice farmers in South Asia, despite conventional narratives that argue otherwise. Figures from India put rice seed replacement rates at 26 % (Seednet 2007). Additionally, while seed saving is an important crop management and livelihood strategy among the poor, it necessarily limits their access to technological improvements embodied in seed. Commercial seed markets are one among several mechanisms through which farmers can access these technological improvements—access that they might forgo if they were to depend solely on own-seed savings or exchanges with neighbors. Although hybrid rice seed is indeed significantly costlier than OPV rice seed (approximately 10 times the price), these costs are partly defrayed by a lower seeding rate.[2]

A second concern that hybridization concentrates market power in the hands of a few companies that are able to breed and market superior hybrids. This concern invokes the notion of "seed security," or that farmer and national dependence on market forces to supply seed increases smallholders' and national vulnerability to monopolistic pricing or other predatory practices by multinational seed companies. Although compelling evidence suggests that some seed markets are highly concentrated in some countries and that corporate pricing strategies may be welfare reducing for farmers in certain instances, the question of market power is essentially an empirical one, requiring careful and context-specific analysis. Even in a country like India, which has a relatively large number of seed companies in the market, a large share of the hybrid seed market is dominated by a small handful of firms. More than 75 % of the total hybrid market (by value) was captured by just five firms in 2008–09—Bayer Cropscience (43 %), Pioneer Hi-Bred International (13 %), Nath Seeds (11 %), Advanta (5 %), and Ganga Kaveri (5 %).

Third is the concern that hybridization leads to greater risk in the form of (1) lower in situ genetic diversity and greater susceptibility to pests and disease and (2) fewer management alternatives to cope with production risks, particularly for smallholders with limited access to credit, insurance, and other services that help manage risk. Again, the extent to which these factors are significant concerns is largely an empirical question that depends on context and situation.

In short, despite criticisms of commercially marketed hybrid seeds for smallholders, the welfare trade-off between farmer-saved seed and farmer-purchased seed, as well as the externalities associated with lost biodiversity, are not as clear-cut as suggested. The specific opportunities, challenges, and risks associated with rice hybrids are discussed in more detail throughout this paper.

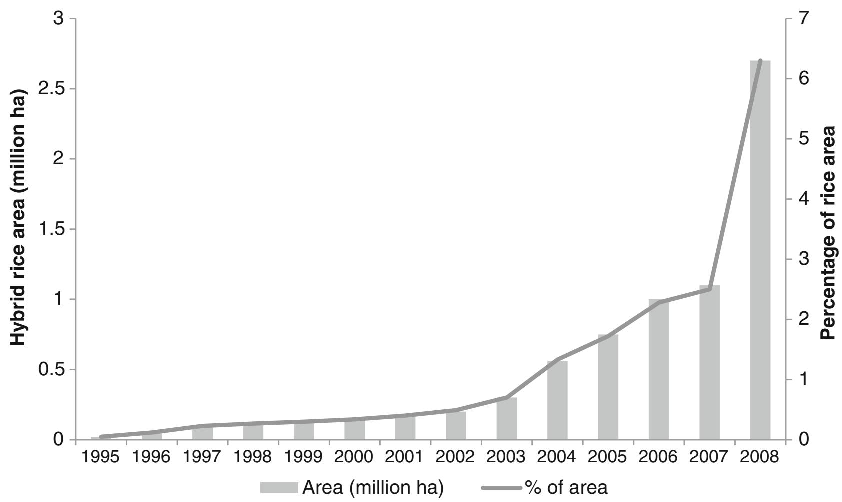
Hybrid rice development in India has been hampered by several nontrivial scientific and technical challenges. From the outset, public- and private-sector researchers have been working with a narrow germplasm base that poses significant constraints on producing marketable hybrids with the yield advantages preferred by farmers and the grain qualities preferred by consumers (Janaiah 2002; Janaiah et al. 2002; Janaiah and Hossain 2003, 2005). An additional challenge has been the multiplication of hybrid rice seed in significant levels of quality and quantity (Xie and Hardy 2009). Although solutions to many of these technical challenges have emerged in recent years, their initial persistence gave hybrid rice a rocky start in India. To better appreciate how the ST&I framework applies to the development of India's hybrid rice market, it is first worthwhile considering the context and experiences of India.

Systematic research on hybrid rice in India only began in 1989 under a relatively small program of the Indian Council of Agricultural Research (ICAR), focusing on hybrids for irrigated cultivation (Janaiah 2002). Subsequent research programs, totaling approximately $8 million, have been funded by the United Nations Industrial Development Organization (UNIDO) and Food and Agriculture Organization (FAO) (1991–96 and 1999–2001), the Mahyco Research Foundation (renamed the Barwale Foundation since 2005) (1997–2000), the Asian Development Bank (ADB) and IRRI (1999–2000), and the National Agricultural Technology Project (funded by the World Bank) and India's Ministry of Agriculture (2003–08). Despite these investments, the development and delivery of hybrid rice in India have faced several challenges that have delayed the government's goal of introducing hybrid rice on 25 % of all cultivated rice area by 2015. As of 2008–09, hybrid rice represented an estimated 6 % of India's 44 million hectares under rice cultivation (Fig. 2), though the area under cultivation increased significantly from 2007 to 2008.

Farmers' concerns about the inferior grain quality, low market price, susceptibility to biotic stress, and poor relative yield gains discouraged many early adopters in the intensive rice–rice systems of south India and the rice–wheat systems of northwestern India in the early to mid-1990s. Janaiah (2000, 2002) provided some of the earliest evidence on the economics of hybrid rice adoption in India with survey data from small samples of households in Andhra Pradesh, Karnataka, Tamil Nadu, Haryana, Orissa (now known as Odisha), Punjab, and West Bengal. Although the sampling frames are insufficiently

[2] Recommended seeding rates ranging from 15 to 30 kg/ha for transplanted hybrid rice, depending on agroecological conditions and other management practices. These seeding rates are generally lower than rates for inbred rice. See Virmani et al. (1998) and Xie and Hardy (2009) for further discussion.

Fig. 2 Area under hybrid rice cultivation in India, 1995–2008. Source: Authors' calculations based on Baig (2009) and Francis Kanoi Marketing Research (2009)



representative and the methods do not sufficiently address potential sampling bias, these early observations do provide some useful insights on those few households cultivating first-generation hybrids in India. Janaiah (2000, 2002) reported that poor quality seed, variable yields, poor adaptation to certain agroecological conditions, susceptibility to pest and disease pressures, and low prices received for inferior quality grain were to blame for poor adoption rates. In general, he concluded that hybrids available in the market at that time were not profitable for farmers in India.

Subsequent efforts to improve breeding and promote hybrids in other parts of India met with mixed outcomes. Despite the breeding improvements and promotional efforts—and, in some places, up to 50 % subsidies on seed—studies reported mixed outcomes from hybrid rice cultivation in 2000–01. Chengappa et al. (2003), Janaiah (2003), and Ramasamy et al. (2003) found that even where hybrids were marginally higher yielding than popular inbred varieties, farmers faced additional challenges that reduced profitability. The higher costs of seed and fertilizer inputs, coupled with the lower market price for hybrid grain due to poor quality and poor rice head recovery during milling, meant that the net returns to hybrid rice were frequently lower than for varieties. Ultimately, farmers abandoning hybrid rice cited a long list of reasons for their discontinued use, including poor grain quality, low market price, high seed cost, nonavailability of quality seeds, susceptibility to pests and diseases, low head-rice recovery, and chaffy or sterile grains.

Despite all this, the proportion of area under hybrid rice has grown at a rate of about 40 % per year since 2005, albeit from a low base (Fig. 2). This has occurred most markedly in four northern and eastern states—Jharkhand, Bihar, Uttar Pradesh, and Uttarakhand—where rice yields are low relative to the national average. In these four states, private hybrids account for more than 95 % of area under hybrid rice cultivation (Baig 2009; Francis Kanoi Marketing Research 2009; Viraktamath and Nirmala 2008). Currently, 80 % of the total hybrid rice area in India is cultivated in Jharkhand, Bihar, Uttar Pradesh, and Chhattisgarh, with smaller areas under hybrid cultivation in Madhya Pradesh, Assam, Punjab, and Haryana (Viraktamath 2011).

Yet hybrid rice is still characterized by a low rate of adoption. According to data from the Francis Kanoi Marketing Research (2009) survey, only 6.3 % of farmers sampled were planting hybrid rice in 2008–09, accounting for only 6.2 % of total area under rice cultivation. Still, the same survey reported that 24 % of surveyed rice farmers in Bihar and 15 % in Uttar Pradesh have tried cultivating hybrid rice at some point in the past. Likewise, according to data from the CSISA baseline survey, 53 % of surveyed farmers in selected districts of Bihar and 15 % in selected districts of eastern Uttar Pradesh have cultivated hybrid rice.[3]

These figures, of course, do not reflect the effectiveness of efforts to promote hybrid rice in India, nor would they allow for analysis of determinants of adoption, since adoption is the result of a conscious decision made by farmers consequential to previous exposure to the technology. As Diagne and Demont (2007) have demonstrated, incomplete diffusion of information about a technology results in nonexposure bias, which implies that the observed proportion of survey sample farmers who have adopted a particular technology does not

[3] Given the high rates of hybrid rice adoption reported in the CSISA baseline survey relative to other sources, it is worth noting possible issues relating to data quality and accuracy. One issue is that although the CSISA baseline survey specifically asked farmers about their familiarity and experience with hybrid rice, it is possible that farmers, enumerators, or both did not accurately distinguish among hybrid rice, high-yielding (modern inbred) rice varieties, and traditional (land race) rice varieties. Alternatively, it is possible that the districts covered by the CSISA baseline survey were characterized by progressive farmers or more vibrant seed and input markets relative to all-India figures, thus resulting in high rates of hybrid adoption. That said, the CSISA baseline survey data are not implausible in light of state-level adoption rates reported by Francis Kanoi Marketing Research (2009).

consistently estimate the true population adoption rate, even in random samples.[4] In India, it seems that diffusion of hybrid rice is incomplete and uneven.

Farmers' awareness of hybrid rice is higher, for example, in northern states (Uttarakhand, Uttar Pradesh, Haryana, and Punjab) and central states (Chhattisgarh and Madhya Pradesh) than in southern or eastern states—figures that correlate with regional adoption patterns (Fig. 3). Surprisingly, poor grain quality and lower market price for hybrid rice grain are not cited among the top five reasons for not growing hybrid rice. Rather, lack of awareness and high cost of seed are the top reasons (Fig. 4). In these northern states, the high cost of seed is the major reason for not adopting hybrid rice relative to the lack of awareness. However, in eastern states such as Jharkhand, West Bengal, and Bihar, as well as Karnataka and Tamil Nadu in the south, both the high cost of seed and lack of awareness are major constraints. Overall, these data indicate that there are significant state and regional differences underlying farmers' rationale for adopting or not adopting hybrid rice.

A relatively new study by Janaiah (2010) provides some insight on adoption determinants with data from a 2008 survey of rice farmers in Chhattisgarh, Uttar Pradesh, and Haryana. In the Janaiah (2010) sample, hybrids still demonstrated a significant (30 %) yield gain and profitability over inbred varieties in the two rainfed eastern states (Chhattisgarh and Uttar Pradesh) and were generally equal in yield and profitability in the irrigated northwestern state (Haryana). An important change, however, was that farmers generally did not perceive grain quality as a serious issue as compared with survey findings on the previous generation of hybrid rice a decade earlier.

Data from the CSISA baseline survey suggest that a wide variety of issues are influencing hybrid rice adoption in India. In addition to information constraints and ambiguity, which constrain farmers' understanding of varietal alternatives, concerns about low yields; poor seed quality (such as concerns over dealers mixing high-quality seed with poor-quality seed); lower profitability (primarily resulting from lower output prices rather than the higher seed price); and susceptibility to pests, diseases, and weeds have led farmers not to adopt hybrids. Even among those farmers who, at some point or another, have adopted hybrids, poor seed quality and low yields have contributed to the discontinued use of hybrid rice within the Indian sample covered in the CSISA baseline survey (Table 3).

These same data suggest that most hybrid rice adopters tend to be relatively wealthy. Nearly 75 % of all hybrid rice adopters in the CSISA baseline sample have incomes above the poverty line, and more than half of all adopters have per capita incomes that fall in the upper-middle or upper income quintiles. In addition, as Fig. 5 illustrates, the proportion of households adopting hybrid rice increases with increasing income. Comparing adoption rates across adjacent quintiles, Table 4 indicates that there is generally a significant pattern of increased adoption rates with higher income. Although this correlation could simply reflect hybrid adoption increasing incomes, there are strong theoretical grounds for wealth or income conditioning hybrid adoption. For example, greater income or wealth is often associated with larger landholdings, greater access to credit (which itself is often a function of an individual's landholdings), and lower absolute risk aversion, all of which are generally observed to facilitate earlier adoption of new (as compared with conventional) technologies such as hybrids (for example, Feder 1980).

An important aspect of the hybrid rice experience in India relates to the role of the private sector, and several trends are worth noting.[5] First, current efforts by the private sector to promote hybrid rice are significant in eastern India, where yields for inbred varieties are already fairly low (roughly 2.5 tons per hectare) and where the potential yield gains from cultivating hybrid rice may be more pronounced.

Second, private-sector efforts have also been significant in areas where the higher yields obtained from hybrids have offset the low prices of all rice in the market. This finding suggests that despite concerns about input costs, grain quality, and consumer acceptance, some farmers are finding it profitable to cultivate hybrid rice. Of course, the relative profitability of hybrid rice is determined not only by input costs and yield, but also by the signals determined by minimum support prices (MSPs) for rice in India, which was increased by 16 % for the 2012–13 non–basmati rice crop. This—coupled with a marked depreciation of the Indian rupee—will change the calculus for hybrid rice farmers and rice farmers in general.

Third, the private sector is launching a new round of what it views as highly competitive hybrid rice lines for the market. Although the private sector accounts for only 20 of the 53 hybrid rice releases in India as of 2011 (Directorate of Rice Development 2011), private-sector products account for the majority of cultivated area under hybrid rice, as well as a significant portion of releases since 2008. Several recent private sector releases have embodied the improvements in grain quality alluded to earlier.

[4] If our objective were to evaluate efforts at promoting hybrid rice in India or to study the determinants of hybrid rice adoption, then pursuing an empirical approach along the lines of Diagne and Demont (2007) would allow us to isolate the average adoption rates among those farmers who had been exposed to hybrid rice, a measure analogous to the average treatment effect from the program evaluation literature. Since we are not attempting to evaluate efforts at promoting hybrid rice or study determinants of adoption, the referenced figures, which do not necessarily characterize the joint distribution of exposure and adoption, do a reasonable job of summarizing the footprint of hybrid rice within the context of Indian rice cultivation.

[5] See Tripp and Pal (2001) for an early mention of the private sector's role in hybrid rice.

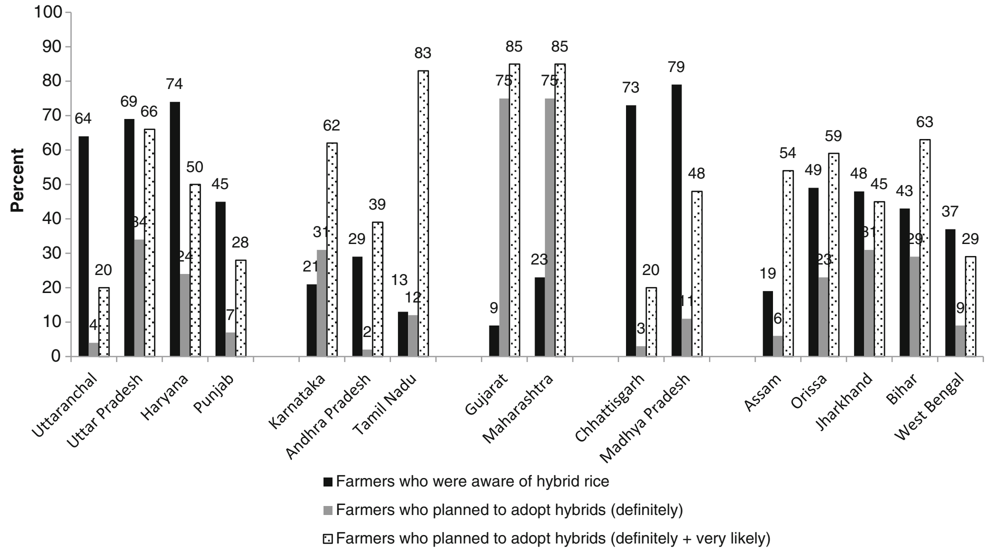


Fig. 3 Awareness of and future likelihood of adoption of hybrid rice in India, 2008–09. Source: Francis Kanoi Marketing Research (2009). Note: Although the state of Uttaranchal was renamed Uttarakhand in 2007, the state is denoted by its former name by Francis Kanoi Marketing Research (2009)

These trends indicate strong potential for growth in India's hybrid rice market, perhaps especially among private-sector actors. The size of the seed market in 2008–09 was estimated at about 35,000 metric tons, with a total value of $142 million (Francis Kanoi Marketing Research 2009). Although no complete estimates exist for the number of companies marketing hybrid rice seed, Kumar (2008) and Viraktamath and Nirmala (2008) estimated that there are between 30 and 60 companies engaged in developing hybrid rice varieties.

Still, the prolonged growth of the hybrid rice market will require further investment in development and delivery to boost its prevalence in farmers' fields. Several firms are investing heavily in R&D to improve yield performance, reduce yield variability, and improve grain quality. Spielman et al. (2011) estimated annual R&D investments by the private sector at $9 million in 2009. In addition, many firms are also investing in the expansion of their marketing and distribution networks (Baig 2009; Francis Kanoi Marketing Research 2009; Viraktamath and Nirmala 2008). At present, there remains a dearth in private dealers providing farmers with access to hybrid seeds. In several states, most hybrid seeds that farmers acquire come from government suppliers, which provide only limited supplies to farmers at subsidized rates. Continued investment in private-sector R&D and delivery mechanisms has the potential to provide significant and sustained growth in the cultivation of hybrids in India.

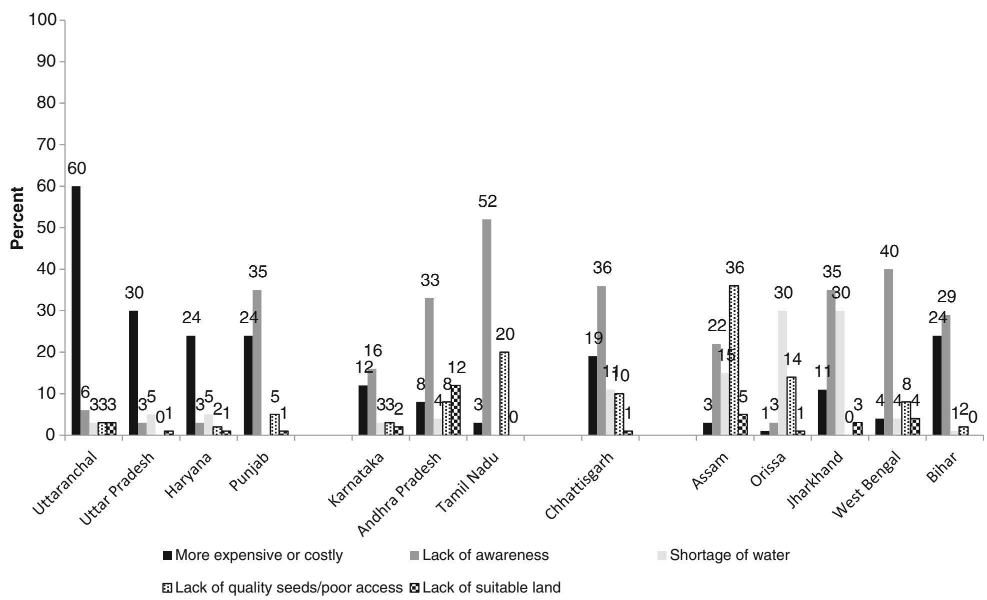


Fig. 4 Top five reasons for not growing hybrid rice in India, 2008–09[a,b]. Source: Francis Kanoi Marketing Research (2009). Notes: (**a**) Lack of information on hybrid seeds, no prior experience in hybrid seed cultivation, and no awareness about hybrid rice are combined together in the "Lack of awareness" category. **b** Although the state of Uttaranchal was renamed Uttarakhand in 2007, the state is denoted by its former name by Francis Kanoi Marketing Research (2009)

Table 3 Constraints to adoption and cited reasons for discontinued use of hybrid rice among CSISA hub domains in India (percentage of qualifying respondents)

Constraint	Never adopted (%)	Discontinued (%)
Capital constraints	0.76	1.91
Information constraints	12.12	7.01
Labor constraints	0.38	1.27
Land constraints	1.52	5.73
Low yield	16.67	26.11
More costly/Less profitable	14.39	8.92
Not popular	17.42	12.10
Others	2.27	3.82
Pests/Diseases/Weeds	13.26	15.92
Poor grain quality	3.79	1.27
Poor seed quality	15.91	15.92
Risk aversion	0.76	0.00
Unsuitable	0.76	0.00

Authors' creation based on data from CSISA (2011)

Future scenarios and challenges for hybrid rice

While there are certainly technical and economic challenges posed by hybrid rice, interest in the technology remains significant in India and South Asia more broadly. Hybrid rice is high on the agenda of many public policymakers and corporate decisionmakers as a means of boosting stagnant yield growth, improving national food security, and raising incomes. Less cited, but of general interest to many, is promoting hybrid rice as a means of sustainable intensification of production on a smaller area of land, allowing for greater diversification into other, higher-value crops. This section analyzes the key challenges associated with hybrid rice in India by drawing on the conceptual framework described earlier. In particular, this section focuses on key constraints related to investment, collaboration, and risk management strategies associated with the stages of discovery, development, and delivery.

Scientific discovery

The challenges facing hybrid rice in India begin at the discovery stage, which is characterized primarily by the fundamental scientific and technical dimensions of the technology. These challenges represent broad classes of problems that are generally addressed over long time horizons and at a precommercial, preregulatory, and predistribution stage. We examine some of these constraints here. For further detail, see Xie and Hardy (2009).

First, researchers have been severely challenged in their efforts to secure high levels of heterosis in hybrid rice. China's impressive levels of heterosis have been developed for temperate-region rice hybrids, whereas India requires tropical hybrids, in which heterosis is generally only 10–12 % over the best inbred rice varieties. An argument can easily be made that better management practices in the cultivation of inbred rice varieties can generate comparable yield gains. As such, the relative yield benefits of hybrids over inbred varieties are not yet significant enough to incentivize widespread transition from varieties to hybrids.

Second, researchers have been constrained by the limited effectiveness of the hybridization systems currently in use. This includes, in particular, the three-line male sterility system

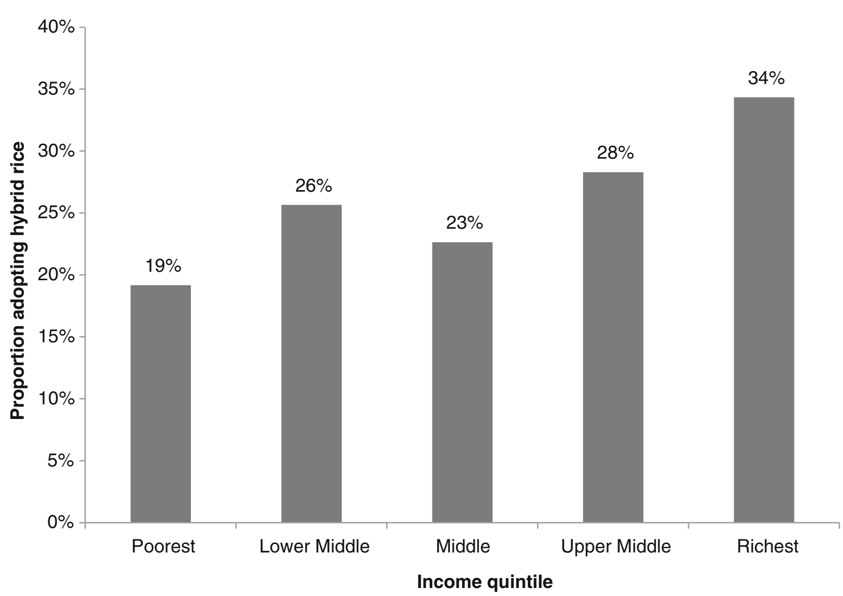


Fig. 5 Hybrid rice adoption in selected districts and states of India, by income quintiles, 2010. Source: Authors' creation based on data from CSISA (2011)

Table 4 Hybrid rice adoption in selected districts and states of India, by income quintiles, 2010

Income quintile	Adoption rate (%)
Poorest 20 %	19.17 (0.394)
Lower middle 20 %	25.66[a] (0.438)
Middle 20 %	22.64 (0.419)
Upper middle 20 %	28.30[b] (0.451)
Richest 20 %	34.34[b] (0.476)

Authors' creation based on data from CSISA (2011)

Standard deviations are provided in parentheses. Significance based on one-tail t-tests of group adoption rates among adjacent income groupings

[a] Significant at 5 % level

[b] Significant at 10 % level

that is most commonly used in India, but also the more advanced two-line system that is used in China. Further development of hybridization systems based on tools of genetic modification and (possibly) chemical hybridizing agents could accelerate hybrid rice research in the long run. In the short run, however, hybrid rice research will still depend on complex and sensitive systems of hybridization for rice.

Third—and of possibly less importance today than a decade ago—is the narrow germplasm base from which hybrid rice research is being conducted, which is in part a result of the limiting reliance on the male sterility system and in part a result of the absence of an effective heterotic genetic pool. This narrow base constrains the efficiency and output of hybrid rice breeding programs and, further down the line, creates high levels of pest and disease susceptibility in cultivated hybrid rice populations. Because of the lack of commercially usable cytoplasmic male sterile lines, development of hybrid rice outside China has been slower than expected (Virmani 1994), which poses difficulties for breeding hybrid rice with improved abiotic and biotic stress tolerance traits, better adaptation to different agroecological contexts, and better cooking and consumption qualities. Efforts to expand this narrow germplasm base are also hampered by China's implicit ban on the export or exchange of its most advanced materials for hybrid rice breeding, including female parental lines used in its superior two-line breeding system. That said, the narrow genetic diversity of female parents that plagued earlier generations of hybrid rice in South Asia is no longer viewed by researchers as the key issue, having been resolved by the creation of new female lines and new techniques for creating such lines.

Fourth, and related to this narrow germplasm base, has been the poor grain quality of hybrids, which initially led to low levels of consumer acceptance. This issue was of particular importance to farmers in high-productivity irrigated areas, who produce marketable surpluses, though possibly less so for farmers in rainfed or otherwise low-productivity areas, who produce for their own consumption. The key issue centered around amylose, the starch molecule that gives milled rice its specific appearance and character after cooking.[6] Although there is significant variation in consumer preferences for rice across India, higher amylose content (above 25 %) is broadly reflective of generalized preferences in the region. In the past several years, researchers have been able to address this constraint, though cultivation of hybrid rice with these improved qualities is still reportedly at relatively low levels.

The general consensus from most scientists is that many of these problems can be readily solved with sufficient time, effort, and resources. However, this also suggests that solutions will not be immediately available or remunerative in commercial markets. Thus, there is a need for both public and private investment in hybrid rice.

As with most crop research—including hybrid crops that are potentially lucrative in downstream markets—an optimal level of upstream public investment is required to translate the science into a viable technology. Public investment in R&D is generally more adept at solving basic problems constraining the effective use of a technology where longer time horizons and pre-commercial application are key characteristics. Where neither private firms nor sovereign governments are willing to invest in removing these constraints—where the public good is global in nature—there is a case for international public investment in R&D efforts.

The international donor community, notably ADB and FAO, has financed hybrid rice R&D at IRRI, which began its research program on hybrid rice for tropical Asia in 1979. In 1988–89, IRRI released the two cytoplasmic male sterile lines, IR58025A and IR62829A, which are still used in most hybrid rice breeding programs in Asia today (IRRI 2005).[7] In 2008, IRRI widened its commitment to hybrid rice research by establishing the Hybrid Rice Development Consortium (HRDC), a global platform designed to support research and share materials with public research agencies, private seed companies, and civil society organizations. Between 2005 and 2010, IRRI transferred more than 7,400 germplasm samples to other hybrid rice researchers around the world, with more than 70 % of those transfers moving through the auspices of HRDC. Germplasm transfers have increased dramatically in recent years, with more than 80 % of total transfers occurring from 2008 to 2010. Material transfers to India represent 33 % of all transfers between 2005 and 2010 (Fig. 6), though 61 % of the total germplasm transfers to India occurred during 2010. IRRI has further expanded its commitment to hybrid rice

[6] Higher amylose content (20–25 % or more) gives cooked rice a high volume and dry quality with well-separated grains, whereas a lower amylose content (below 20–25 %) gives cooked rice a moister, stickier quality (IRRI 2012).

[7] For example, IR58025A is the female parent for popular Indian hybrids such as PHB 71 marketed by Pioneer Hi-Bred International.

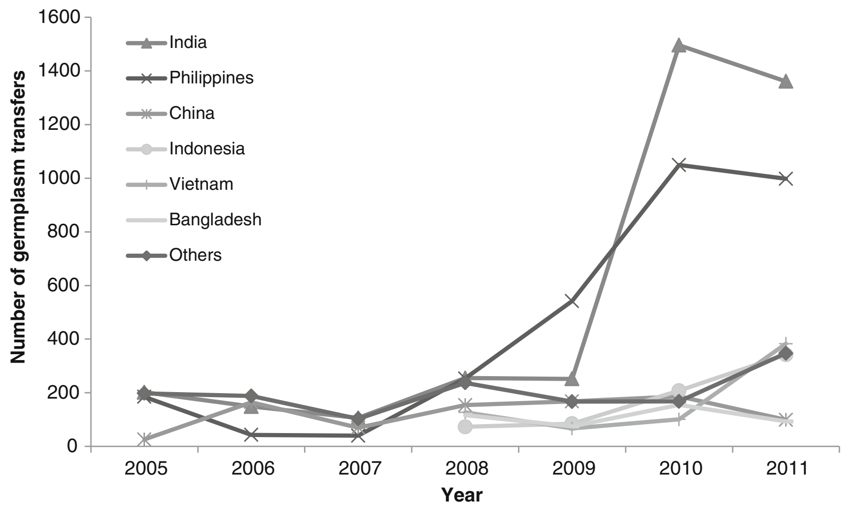


Fig. 6 Germplasm transfers from IRRI's hybrid rice research program, by country, 2005–2011. Source: Fangming Xie, IRRI (personal communications), 2012

research under the Global Rice Science Partnership (GRiSP), with a planned investment estimated at $15–17 million for South and Southeast Asia over 5 years; this figure does not include the related rice breeding work undertaken in other GRiSP components nor other IRRI programs that also support hybrid rice research or investments made by national partners (IRRI/AfricaRice/CIAT 2010).

Hybrid rice research has arguably suffered from donors' short-term outlooks and project funding cycles. Although some resources were allocated to public-sector research at both the national and international levels, there is a sense among many scientists that a disproportionate share of the funding and scientific effort was allocated to capacity strengthening, demonstrations, and dissemination activities, all built around a limited set of hybrids and hybrid parent lines. In short, these funding commitments likely impeded early and rapid progress in addressing the technical challenges outlined above. This then raises the question of the private sector's role in hybrid rice research. Private investment has been central to problem solving in India, with multinational companies such as Bayer CropScience and Pioneer Hi-Bred International playing leading roles. But private sector investments are not likely to fill the funding gap. Private-sector spending on hybrid rice research in India is in the order of $5–12 million per year, but these investments are just a small fraction of the private sector's overall global R&D investment portfolio.[8]

Despite the constraints imposed by insufficient investment in hybrid rice research, the collaboration strategies being formed around hybrid rice are worth noting. IRRI's HRDC is a critical platform for collaboration between public research agencies and private seed companies on various aspects of hybrid rice research. IRRI's long-standing relationship with pivotal agencies in China's national agricultural research system is also a critical input to making expertise and materials available to consortium members and IRRI's partners. In addition, IRRI's forward-looking policies on intellectual property and public–private partnerships provide an avenue for supporting effective collaborations with firms that are willing and able to invest in hybrid rice. Although more rigorous evaluations of these various collaboration strategies are needed, there are strong indications of a relevant architecture for translating hybrid rice science from the public sector into viable hybrid rice technologies in the private sector.

One significant risk related to hybrid research in the discovery stage is associated with the use of tools derived from biotechnology—particularly genetic modification (GM)—in the development of improved hybridization systems. These hybridization systems are almost exclusively being developed in the private sector, with large multinational crop science firms taking the lead in their development. The associated risk relates to the nascent state of biosafety regimes in many Asian countries and the possibility that the use of GM-based hybridization systems cannot be effectively evaluated under current regulatory regimes. If this is the case, it is possible that biosafety regulators could revert to a "precautionary principle" that inhibits the introduction of hybrid rice derived from GM-based hybridization systems.[9]

A related risk comes from the long-term value of hybrid rice as a practical platform for launching GM traits in rice. Hybridization provides innovators with a biological form of IPR protection, because farmers have to purchase seed each season to realize the yield gains conferred by heterosis. Not only does this allow innovators to recoup their R&D investments in rice improvement, but it also creates an effective platform for continuous investment in developing GM rice traits. Moreover, because firms can easily monitor their sales of hybrid rice seed, they gain a means of monitoring farmers' trait preferences, on-

[8] By way of comparison, consider that current global investment for maize research is in the order of $1.5 billion, and primarily from the private sector.

[9] For example, this precautionary principle was applied to Bt eggplant in India. Although Bt eggplant had reached the advanced stages of India's regulatory process in 2009, its release became the subject of an indefinite moratorium in 2010.

farm performance, and crop management practices, thus providing vital informational feedback mechanisms needed to support continued improvements and effective stewardship. However, the risks associated with the nascent or controversial biosafety regulations in some developing countries can limit the realization of this long-term value in hybrid rice.

Technology development

Solutions to the scientific and technical problems discussed earlier would encourage more serious investment by the private sector in hybrid rice product development. However, product development itself faces several key challenges that need to be addressed if hybrid rice is to generate welfare-improving and yield-enhancing impacts in India.

A major difficulty facing hybrid rice is the production of high-quality hybrid seed. Technical requirements for hybrid seed production are sensitive, requiring careful management of breeding materials and the seed farms themselves. Unlike varietal rice, it is difficult to outsource hybrid rice seed production to smallholders, smallholder cooperatives, or community and village seed production schemes. The technical requirements for hybrid rice seed production represent a costly constraint on the production of marketable quantities of seed for all but the largest, most technically advanced, or well-capitalized seed companies in the market.

A second challenge is the protection of the intellectual property embodied in the seed. Private investment in seed-based technologies is partly determined by the existence of a credible IPR policy regime. Although hybrids provide the innovators with a biological form of IPR protection, these biological IPR protections are more effective when backed by some form of legal protection. This is particularly valuable in situations where it is easy for competitors to steal parental lines from foundation seed and production fields, as is the case in both industrialized and developing countries. By ensuring that innovators have legal recourse allowing them to appropriate a portion of their innovation rents, plant variety protection (PVP) laws can incentivize private investment in hybrid rice development. In addition, through related requirements of disclosure, certification, and labeling, PVP laws can help address information asymmetries between farmers and seed retailers. Unfortunately, there is a dearth of sufficiently credible PVP laws in the region. India's Protection of Plant Varieties and Farmers' Rights Act of 2001 provides the region's highest standard of protection, and the large number of PVP applications submitted by the private sector for PVP certificates indicates that innovators take legal protections seriously. It remains to be seen, however, whether the Indian courts are sufficiently able to adjudicate infringement cases in a timely manner. Other regulatory and risk management challenges that must be addressed include streamlining of field testing procedures; improving seed certification, particularly the system of traceability from sole reliance on morphology to one that also incorporates the use of molecular markers; and strengthening the enforcement of PVPs so that spurious seed, copycats, and stolen breeding lines do not enter the market.[10]

Another regulatory issue emerges around the issue of competition and industry concentration. In India and most other South Asian countries, the formal rice seed market is largely concentrated around the high-volume, low-margin varietal end of the business. Only a few firms have entered the high-value, high-potential segment of the market with hybrid rice seed. With such a small number of companies in the hybrid segment, there are concerns that companies operating within such oligopolistic conditions will be able to exert a high degree of market power over farmers. This concern is often voiced in India—even though the Indian hybrid rice market is host to a relatively large number of companies (Spielman et al. 2011). Continuous and careful analysis of market conditions, including competition and concentration, backed by effective enforcement of antitrust laws are necessary to ensure that seed markets remain competitive.

The risk management issues of using hybrid rice as a platform for transgenic traits become more acute when considered at the product development stage. Risks are associated with individual traits conferred on hybrid rice (such as insect resistance or drought tolerance), stewardship of transgenic hybrid rice lines, gene flow issues to wild relatives, pollen flows to other rice varieties such as high-value basmati, and other such concerns. Given the recent experience with Bt eggplant in India, it is difficult to conclude that India has a credibly functional regulatory regime that provides adequate risk assessment and management for transgenic crops. Although many experts interviewed for this study indicated that the Bt eggplant moratorium was not affecting private-sector decisions on investment in transgenic traits, it is unclear whether this will continue to be the case if government capriciousness continues to be high. Creating a transparent regulatory environment to address these issues is therefore critical to the commercialization of hybrid rice containing potentially beneficial GM traits.

Product delivery

Product delivery is possibly the weakest element in the hybrid rice innovation process. Despite its rapid and widespread adoption in China, hybrid rice has not caught on in a dramatic fashion in India. Following initial hybrid release in 1994, farmers in Andhra Pradesh, Tamil Nadu, and Karnataka complained of inconsistent yield performance, low grain quality, high susceptibility to pests, and other factors that led to significant levels of rejection and discontinued use (Janaiah 2002). Since then, hybrid rice has found its way to the more

[10] Several experts interviewed for this study suggested that of the more than 100 hybrids in circulation in India, many are imitations and copycats of the popular commercial hybrids from Bayer CropScience and Pioneer Hi-Bred International mentioned earlier.

marginal agroecologies and markets of northeastern India, where the yield differentials against varieties in common use are more visible to smallholders.

Ultimately, the delivery and adoption of hybrid rice will depend on improvements made in the discovery and development stages. Although hybrid rice has immense potential for increasing productivity and improving overall welfare for the poor in India, the challenges are not insignificant. Important challenges include increasing both seed and grain quality and customizing varieties to various agroecological conditions and consumer preferences. Addressing the challenges of grain quality and customizing hybrids to consumer preferences have important implications for the output prices that farmers receive for their grains. At present, the price penalty on hybrid rice at the farmgate places it at 10–20 % less than coarse grain rice in India. Although breeders have made progress in customizing hybrids to consumers' preferences, the new hybrids coming on the market will need to overcome this price penalty to encourage adoption. Feedback mechanisms between the delivery, discovery and development stages can facilitate these improvements. Further research is required to better understand the factors that motivate or constrain farmers' adoption of hybrid rice. Understanding these factors will help not only inform future discovery and development, but will also provide insight into potential policy responses that can accelerate the widespread adoption of hybrids.

Conclusions and policy recommendations

This paper examines the processes and policies that encourage effective public and private investment in hybrid rice benefiting poor farmers in India. The paper identifies the roles of various organizations involved in advancing hybrid rice development and delivery and examines alternative incentives for enhancing the level and effectiveness of public and private investment in hybrid rice discovery, development, and delivery.

Several policy innovations could accelerate the discovery, development, and delivery of hybrid rice technology in India. First and foremost is the recommendation for further public investment in the upstream research to develop the tools and technologies needed to advance hybrid rice. International and national funding for public research that address improved hybridization systems, grain quality, adaptation of hybrids to local agroecological conditions, and germplasm diversity can provide the platform for more applied plant breeding to develop improved hybrids by both the public and private sectors.

Second is the need to improve the innovation incentives that may ultimately encourage more private investment in hybrid rice development. Stronger IPR policies and enforcement could encourage the entry of complementary private investment, while other policy incentives could accelerate the dissemination and commercialization of public research on hybrid rice that is sitting on the shelf or otherwise confined to academic use.

At the same time, more creative approaches to funding hybrid rice research are needed to provide long-term and sustained private funding for hybrid rice research. One example is a unique foundation-based funding experiment in India. The Barwale Foundation (formerly the Mahyco Research Foundation) is a nonprofit organization that promotes research, technology, and knowledge in the areas of agriculture, healthcare, and education for human welfare (Barwale Foundation 2009). The foundation's investment in hybrid rice research—one of the organization's five in-house research projects—illustrates how private-sector research can be geared toward supporting more applied research and product development. Barwale's research agenda includes a number of activities essential to hybrid rice breeding, such as identification of fertility restorer lines and cytoplasmic male sterility sources, molecular tagging and mapping, and the multiplication and distribution of IRRI germplasm.

Careful attention must be given to the use of public resources to subsidize hybrid rice seed and complementary inputs. Although subsidies have strong historical precedence in encouraging the adoption of new technologies in India, experience suggests that such price distortions can lead to rent-seeking behavior and elite capture among certain types of farmers and industries, thus impeding market growth and efficiency in the long run.

Another set of policy recommendations relates to the future of hybrid rice as a platform for pro-poor GM crop development in India. India's experiences with cotton provide an interesting comparison. The introduction of cotton hybrids and a GM insect-resistance trait (Bt) occurred almost concurrently, resulting in a large-scale transformation of the Indian cotton sector. Although rice is primarily a food crop for own consumption and for sale to the market among smallholders in India, and although cotton is primarily a fiber crop for sale in well-defined markets, similar technological trajectories might be drawn in years to come. This outcome depends acutely on the design and implementation of credible regulatory regimes to manage the risks associated with biotechnology and GM crops.

Hybrid rice has the potential to transform rice cultivation in India. The basic outcome of stable, better adapted, and commercially accessible hybrid rice could translate into a range of positive impacts: enhanced rice productivity; increased on-farm incomes for smallholders; and reductions in the land required for intensive rice production, which in turn would allow for reallocation to other agricultural and nonagricultural activities. The process of innovation, however, is far from complete. Significant scientific, technical, and policy challenges exist at each stage of the innovation process—discovery, development, and delivery—and repeated iterations of research and development need to be pursued. The ability of public policymakers, corporate decision makers, scientists, entrepreneurs, and farmers to understand these challenges and anticipate solutions is fundamental to the long-term prospects for hybrid rice in India.

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