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Submitted Article

Public Incentives, Private Investment, and Outlooks for Hybrid Rice in Bangladesh and India

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Abstract *The governments of Bangladesh and India have set impressive targets to expand hybrid rice cultivation as part of their national food security strategies for the next decade. Although hybrid rice offers significant yield improvements over varietal rice, adoption by farmers remains low and unstable. This paper analyzes the technical challenges, market opportunities, and policy constraints associated with hybrid rice in both countries. It argues that while many of the technical constraints can be addressed through continued investment in breeding, significant challenges remain relating to product development, marketing, and economic policy. Solutions require new insight into relationships between industry structure, business strategies, and public policy incentives.*

Key words: Hybrid rice, agricultural research and development, technological change, innovation, India, Bangladesh.

JEL codes: Q16, Q18, O31, O33.

Introduction

Since the world food price crisis in 2007–2008, many policy makers and donors have turned their attention toward agricultural productivity growth, food security, and technological change. Particular attention has been given to technological solutions aimed at increasing the growth rate of food staple yields, many of which have experienced stagnant or declining growth rates in recent years. Hybrid rice may be one such solution, and prior research suggests that the higher yields attributable to hybrid rice may contribute significantly to improving food security in developing countries where rice is the primary staple (Lin and Pingali 1994; Janaiah, Hossain, and Husain

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2002; Xie and Hardy 2009; Li, Shin, and Yuan 2010). The expected impacts of hybrid rice follow a fairly standard set of impact pathways. First, higher yields can increase the quantity of rice available for own-consumption by farm households that cultivate rice, a benefit that can directly increase caloric intake. Second, higher yields can provide these same households with larger marketable surpluses of rice and thus higher incomes with which to purchase food or other consumption goods. Third, higher yields can increase the national supply of rice in a manner that reduces or stabilizes prices for both urban and rural food-insecure households. Fourth, higher yields can allow for land to be reallocated to other agricultural and nonagricultural uses that generate higher incomes for both the rural and urban poor.

To a large degree, many of these benefits have already been realized in China, where the widespread adoption of hybrid rice is credited with feeding an estimated 60 million additional people per year and reducing the land allocated to rice production by 14% since 1978 (Li et al. 2010). Despite China's success, however, the diffusion of hybrid rice has been much slower in South Asia where overall growth in rice yields has been slow in recent decades (Janaiah et al. 2002; Janaiah 2005). In India and Bangladesh, hybrid rice cultivation accounts for less than 10% of total area under rice cultivation, while in Nepal, Pakistan, and Sri Lanka the prevalence is far lower (Pandey and Bhandari 2008; Spielman et al. 2012).

The potential gains from hybrid rice originate from the expression of heterosis or the increase in yield, uniformity, or vigor of rice 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) is planted, thus compelling farmers to purchase new F1 seed each season if they want to continually realize these yield gains. This contrasts with traditional or modern inbred rice varieties, from which harvested grains can be stored and used as seed in the following year. The unique characteristics of hybrids has been a driving factor behind investment in crop improvement for maize and several other crops in both industrialized and developing countries (see Fuglie et al. 1996; Morris 1998;Fernandez-Cornejo 2004; Pray and Nagarajan 2010).

Despite the lucrative benefits of hybrids to both firms and farmers, there is much criticism of the potential role for hybrids in smallholder-based developing-country agriculture. There are concerns that seasonal or annual purchases of hybrid seed are too costly for many resource-poor, small-scale farmers in developing countries (Kuyek 2000). There are concerns that the technology's complexity poses a barrier to entry, which allows for concentration of market power in the hands of a few companies that are able to breed and market superior hybrids. There are also concerns 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.

While these concerns are valid, they ultimately boil down to empirical questions. Can farmers afford to purchase costly hybrid rice seed? Are hybrid rice seed markets highly concentrated? And does hybrid rice cultivation put farmers and the environment at risk? Developing the evidence needed to answer these questions requires a more concise understanding of

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the evolution and performance of the technology. As we demonstrate in this paper, few answers are as yet forthcoming because, at this early stage, there are still major challenges constraining the widespread adoption of hybrid rice in South Asia. These challenges include not only technical barriers associated with a complex technology but also institutional challenges that require strategic interventions from the government to encourage, rather than inhibit, hybrid rice development and an appropriate role for the private sector. This article aims to address these challenges using a conceptual framework developed in the innovation systems literature to open the "black box" of the research production function and examine the processes behind the product. Specifically, the paper explores the factors that have encouraged or inhibited the development and delivery of hybrid rice in South Asia, with a particular emphasis on the experiences of India and Bangladesh. From this analysis, the paper identifies areas in which public policy and investments can accelerate the development and delivery of hybrid rice.

The remainder of this article is organized as follows. In the following section, we introduce the conceptual framework that underlies this study, followed by a section discussing the data and data sources. The fourth section examines the innovation processes and outcomes related to hybrid rice in India and Bangladesh. The fifth discusses policy options to strengthen these innovation systems and accelerate hybrid rice adoption, followed by conclusions.

An Innovation Systems Approach

In its broadest terms, an innovation system describes the process through which heterogeneous agents transform knowledge into socially or economically relevant use (Freeman 1988; Lundvall 1988, 1985; Edquist 1997). An innovation systems approach elaborates on the complicated interplay among (1) actors, assets, and processes engaged in the production, exchange, and use of knowledge; (2) the actions and interactions among these actors; and (3) the policy incentives, social norms, and economic institutions that influence their actions and interactions (Spielman 2006). In the context of developing-country agriculture, an innovation system describes processes that run counter to the simple linear process of technological change in which new products or services are transferred from scientist to extension agent to farmer (Biggs 1990; Hall et al. 2001; World Bank 2012).

In the context of hybrid rice, this approach moves the discussion beyond a study of technical constraints identified by scientists working on topics such as reproductive biology, disease and pest resistance, and yield (Virmani, Siddiq, and Muralidharan 1998; Virmani 1994; Xi and Hardy 2009) and beyond social scientists working on topics such as constraints to adoption by farmers and consumers (e.g., Janaiah 2000, 2002, 2003; Janaiah and Hossain 2003). Rather, the approach focuses attention on the processes by which science is translated into viable technologies and, ultimately, into commercial products, and on the incentives that motivate individuals, firms, and governments to invest in these processes.

In particular, the approach analyzes four sets of actors that participate in a loosely defined hybrid rice innovation system: international agricultural research centers, national research organizations, private crop science and seed firms, and farmers. The approach further examines their actions and

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interactions, including responses to price signals, investment priorities, collaboration strategies, and other elements that are further categorized below. Finally, the approach addresses public priorities that drive hybrid rice innovation, social and cultural norms associated with shared consumption preferences, and the interplay between markets and state interventions to address market failures. Together, this analysis helps to frame the discussion on hybrid rice from an innovation systems perspective.

Our conceptual framework draws on several prior studies to apply this perspective in a meaningful way. First, it uses an analytical approach described by Sumberg and Reece (2004) who reformulate the problem of agricultural research and technology development for smallholder farmers using concepts from the innovation systems and new product development literature. Second, it builds on prior work that examines the role of both public and private investment in technological change, for example, a study by Gerpacio (2003) who examined the roles of the public and private sectors in promoting hybrid maize in Asia, a partial analog to the hybrid rice storyline we develop here. Third, it responds to a call from Reardon and Timmer (2012) for better analysis of how farmers, firms, entrepreneurs, and intermediaries engage in complex agricultural value chains involving production, processing, and marketing.

We combine these insights to analyze investment, collaboration, and risk management strategies that define the critical decision-making points for translating science into new technologies and viable products through three iterative stages of analysis—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, which are influenced by the economic behavior of individuals, firms, and governments. 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 toward optimal outcomes, innovators face greater levels of uncertainty. This uncertainty necessarily constrains the assessment of whether, or to what degree, 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 science, technology, and innovation.

Necessarily, these differentiated stages overlap, a reality that draws attention to the fact that innovative opportunities cannot be exploited simply on the basis of a linear process that moves from upstream science to downstream application. Based on these ideas, the underlying conceptual framework of this paper is as follows. First, we describe technological change as a process that initially occurs within innovation markets, or markets where intermediary scientific and technical products are exchanged between firms. Innovation markets are commonly characterized by (1) significant levels of knowledge intensity that require sizable investment in research

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Table 1 Key stages and strategies in a science, technology and innovation 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

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and (2) barriers to entry associated with both fixed production and regulatory costs (Brennan et al. 2005). Companies that participate in these innovation markets include commercial entities engaged in "upstream" research and development activities, for example, crop science firms, technology providers, and firms that integrate breeding with production and marketing activities.

Second, we characterize technological change as a transition of knowledge from innovation markets to product markets, or markets where commercial technologies are exchanged in the form of goods and services. Companies operating in the product market include firms engaged in "downstream" seed production and marketing activities. The downstream segment often includes small- and medium-sized enterprises facing relatively low capital requirements and operational costs.

Third, we assume that governments intervene in these markets to simultaneously encourage innovation, inhibit anticompetitive behavior among firms, and increase the participation of end-users in a competitive market (Naseem, Spielman, and Omamo 2010). This balancing act requires that governments have sufficient evidence on which to base policies and investments that simultaneously address productivity growth and welfare improvement priorities. In order to gather such evidence for policymaking, governments require, at a minimum, (1) characterization of the heterogeneity among firms in the innovation and product markets, (2) characterization of industry structure and conduct, and (3) an analytical sense of how public policies and regulations influence innovation, competition, and welfare.

Finally, this body of evidence can be used to construct alternative scenarios in which industry attributes, strategic corporate behavior, and public policy affect the balance between a socially desirable rate of innovation, on the one hand, and the development of a competitive market for products and services that embody innovation, on the other hand. A better understanding of how policies influence an industry's structure and conduct, and how these resulting attributes contribute to (or hinder) innovation and productivity growth can, in turn, improve both industry performance and the delivery of new technologies in developing-country agriculture. Factors such as strategic corporate behavior and public policy on innovation can affect the balance between a socially desirable rate of innovation and a socially desirable distribution of the gains from innovation among consumers, farmers, and innovators. Although this topic is a focus of extensive inquiry in many industrialized countries, only a handful of researchers have recognized its importance in the context of Asian agriculture.

Using this broad conceptual framework, this paper considers the following questions in order to evaluate the evolution of hybrid rice in South Asia. First, how do market signals and public policies incentivize innovation in the hybrid rice seed industry? Second, how do these signals and policies influence the structure and conduct of the industry? Third, what are the developmental and distributional implications of the industry's growth?

Data and Data Sources

Data and analysis were extracted from a range of sources, including peer-reviewed journal articles, government statistical reports, commercial databases, and documents from industry sources. Key sources are as follows.

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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 (with specific reference to rice, wheat, and maize), 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.

Commercial data set. Data were also obtained from a survey conducted by a commercial entity—the Francis Kanoi Marketing Research Group—on rice cultivation in India during 2008/2009. 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.

Household surveys. Household-level data presented in this paper were drawn from two sources: the Bangladesh Integrated Household Survey (BIHS) and the Cereal Systems Initiative for South Asia (CSISA) Baseline Household Survey. The BIHS was conducted by the International Food Policy Research Institute in late 2011 as part of the Bangladesh Policy Research and Strategy Support Program (Ahmed et al. 2013). The BIHS contains data on 5,503 households drawn from 64 districts in the seven primary divisions and is representative at both the national and divisional levels. The survey covers topics that are standard to most income and expenditure surveys in developing countries, as well as topics related to agricultural production, plot utilization, input use, and postharvest management. The

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

Source: Authors' creation.
[a] *Includes representatives of industry associations.*
[b] *Includes researchers from CGIAR.*
[c] *Includes representatives of donor agencies, international organizations, charitable foundations, and nongovernmental organizations.*

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CSISA 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 (Pede et al. 2013). The survey utilized a stratified random sampling frame to survey 2,627 households located in villages drawn from districts and blocks located within the project's coverage area in Bangladesh, India, and Nepal. Although not nationally or regionally representative, the sampling strategy is such that the samples are intended to be representative of the villages included in the project hubs' different domains. The survey contains comprehensive information on many aspects of agricultural production and technological adoption. The data and information presented in this article are drawn primarily from a sample of districts in which CSISA operates in India, specifically in Bihar, eastern Uttar Pradesh, Haryana, and Tamil Nadu.

Hybrid Rice Innovation Systems in India and Bangladesh

There are noticeable differences in how the hybrid rice innovation systems in India and Bangladesh have evolved over time. This section examines the origins of hybrid rice innovation systems and the market performance of hybrid rice in India and Bangladesh, drawing on the primary and secondary data sources described above.

The Origins of Innovation in Hybrid Rice

Hybrid rice research in India and Bangladesh began very differently. Indian scientists were, in fact, the first to identify and document heterosis in rice with research conducted during the 1950s at the Central Rice Research Institute in Cuttack, Orissa (now known as Odisha) (Sampath and Mohanty 1954). Yet systematic research on hybrid rice in India only began in 1989 under a relatively small program of the Indian Council of Agricultural Research focused on hybrids for cultivation in irrigated conditions (Janaiah 2002). Subsequent research programs have received funding from a range of international development organizations, multilateral and bilateral donors, charitable foundations, and the government of India, with investments totaling approximately US$8 million between 1991 and 2008. In Bangladesh, somewhat smaller allocations of funding for hybrid rice research were provided by similar sources to the Bangladesh Rice Research Institute (BRRI) beginning in 1993.

The international donor community, notably the Asian Development Bank and the Food and Agriculture Organization of the United Nations (FAO), has also financed hybrid rice research at IRRI, which began its research program on hybrid rice for tropical Asia in 1979 (IRRI 2005). 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 through 2010. IRRI further expanded its commitment to hybrid rice research under the Global Rice Science Partnership (GRiSP),

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with a planned investment estimated of US$15–17 million for South and Southeast Asia over five years.[1]

Despite similar support from the international system, the Indian and Bangladeshi experiences with hybrid rice differ. India has invested slowly but steadily in hybrid rice breeding and attracted substantial private sector investment. In India, a combination of domestic firms and subsidiaries of multinational firms dominate the hybrid rice seed market, which was estimated to have a total value of US$142 million and a volume of 35,000 metric tons in 2008/2009 (Francis Kanoi 2009). More than 75% of the value in this market was captured by just five firms in 2008/2009—Bayer Cropscience (43%), Pioneer Hi-Bred International (13%), Nath Seeds (11%), Advanta (5%), and Ganga Kaveri (5%). Many of these firms are investing in research to further improve yield performance, reduce yield variability, improve grain quality, and strengthen their marketing networks (Viraktamath and Nirmala 2008; Baig 2009). Annual R&D investments in hybrid rice development by the private sector were estimated at US$9 million in 2009 (Spielman et al. 2012).

By contrast, the introduction of hybrid rice in Bangladesh emerged from crisis rather than scientific investment. Hybrids were first introduced in Bangladesh in 1998/1999 when floods caused a shortfall in domestic seed supply, in response to which the government allowed private companies to import 2,000 metric tons of hybrid seed (Azad et al. 2008). These first hybrids were introduced for the dry-season irrigated *boro* rice crop and were sourced primarily from China. Encouraged by the yield gains offered by hybrid rice, the government of Bangladesh prioritized research on better hybrids for the country soon after the crisis. BRRI led the research effort with technical support from IRRI, financial support from the Bangladesh Agricultural Research Council (BARC), and project funding from the World Bank, FAO, and others (Ar-Rashid, Julfiquar, and Ali 2011).

Yet in spite of these research investments, the supply of hybrid seed in Bangladesh still depends primarily on bulk seed imports from China and possibly on unverifiable quantities of seed smuggled into the country from neighboring India (Ar-Rashid, Ali, and Gisselquist 2012). Only since 2010 have there been signs of adaptive research and product development being undertaken domestically. Firms such as Supreme Seed Company, Lal Teer Seed, and Advanced Chemical Industries have begun importing parental lines from China to enable domestic hybrid seed production, while BRAC, a large nongovernmental organization and a leader in the hybrid rice seed market, is making similar investments in hybrid rice research.

Another revealing figure that differentiates the paths taken by these two countries is the number of germplasm transfers from IRRI. Notably, less

[1]*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. GRiSP's long-term goals aim at the adoption of new hybrid rice with at least a 15% yield advantage. Specific GRiSP milestones for hybrid rice in South and Southeast Asia are as follows: 50 new breeding populations developed and distributed to partners by 2011; 5,000 new hybrid parents and hybrids test-crossed and evaluated at IRRI and other locations by 2013; and 10 new hybrids released for commercial production by public or private sector partners by 2015. Budget estimates are for both South and Southeast Asia, based on an assumption that hybrid rice is allocated an equal (17 percent) share of funding among the six subthemes under Theme 2: "Accelerating the development, delivery, and adoption of improved rice varieties." See IRRI/AfricaRice/CIAT (2010).*

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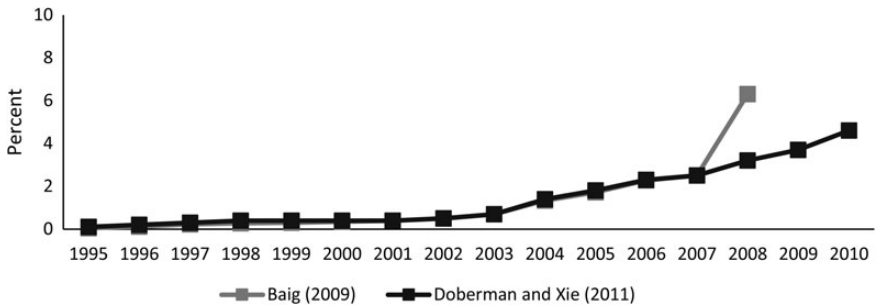
than 5% of IRRI's total germplasm transfers have gone to Bangladesh, reflecting Bangladesh's heavy dependence on material and seed transfers from China for hybrid rice research and product development. This contrasts starkly with transfers to India: material transfers to India represent 33% of all germplasm transfers between 2005 and 2010, with 61% of total germplasm transfers to India occurring during 2010.

The On-Farm Performance of Hybrid Rice

In spite of their different approaches to product development, both countries have experienced fairly similar challenges with respect to farmers' adoption of hybrid rice. As of 2008, hybrid rice represented an estimated 3% to 6% of India's 44 million hectares under rice cultivation (Baig 2009; Doberman and Xie, personal communication 2011) (Figure 1). As of 2007/2008, hybrid rice represented an estimated 8% to 10% of Bangladesh's 11 million hectares under rice cultivation. But when viewed as a share of rice cultivation during the dry winter season—a season that accounts for over half of rice production in Bangladesh—hybrid rice cultivation peaked in the 2007/2008 season at somewhere between 17% and 22% total area under *boro* rice cultivation, although the rate dropped steadily thereafter (Ar-Rashid et al. 2011; BBS 2011; Doberman and Xie, personal communication 2011) (Figure 2).

So what explains these variations in adoption rates between India and Bangladesh, and between successive years? Part of the story may lie in the simple economics of production and the returns to cultivating hybrid rice. On the cost side, several studies suggest that hybrid rice cultivation does not impose substantially higher total production costs on farmers. Higher seed costs and higher levels of fertilizer and pesticide use are generally offset by lower seeding rates (i.e., the amount of seed required to cultivate a given area of land) and lower irrigation costs associated with hybrids' early maturation compared to other modern varieties (Azad, Mustafi, and Hossain 2008; Hossain 2008). On the revenue side, while hybrid rice yields are generally 15%–30% higher than the yields of many other modern inbred varieties in the target agroecologies of India and Bangladesh, farmgate prices in both countries for hybrid rice grains fall 10%–20% below the price for other coarse rice varieties.

Figure 1 Hybrid rice as a share of total area under rice cultivation in India, 1995 to 2010 (percent)



Source: Authors, based on data from: Baig (2009) and Achim Doberman and Fangming Xie, International Rice Research Center (pers. comm., 2011).

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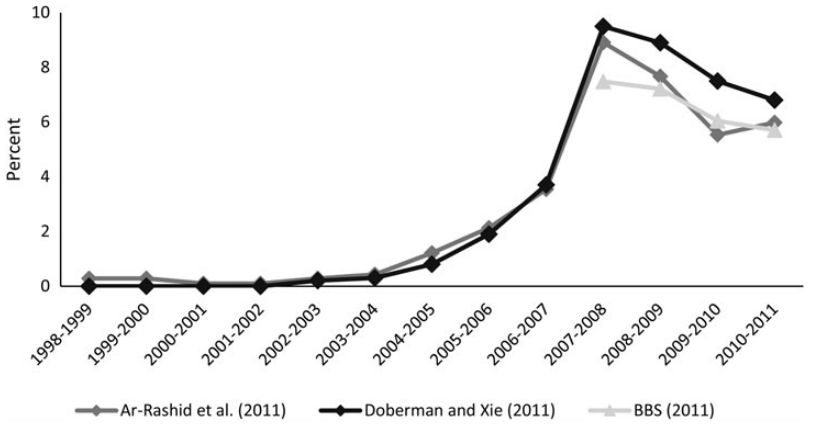
Figure 2 Hybrid rice as a share of total area under rice cultivation in Bangladesh, 1998–99 to 2010–11



Source: Authors, based on data from: Ar-Rashid et al. (2011); Achim Doberman and Fangming Xie, International Rice Research Center (pers. comm., 2011); and BBS (2011).

The Market Performance of Hybrid Rice

It is this latter market response from millers, traders, and consumers that is most telling about the technology's performance. A number of studies in both countries point out that certain consumption qualities of hybrid rice—taste, stickiness, consistency after being cooked and set aside, and tendency to shatter during milling—are inferior to more popular inbred varieties (Azad et al. 2008; IRRI 2012).[2] In 2012, the state government of Punjab, India, went so far as to ban the cultivation of hybrid rice in the state, primarily in response to millers' complaints about its quality (Hindustan Times 2012).

These qualities translate into low farmgate prices for hybrid rice grain on the order of anywhere from 5% to 20% less than the farmgate or public procurement prices for inbred rice (Janaiah 2000, 2002; Ramasamy et al. 2003; Spielman et al. 2012). That said, there are recent indications that the consumption quality gap is narrowing (Janaiah 2010), and several companies are boasting about the release of next-generation hybrids with more desirable consumption qualities.

The market performance of hybrid rice has also been constrained by socio-cultural dimensions of rice, particularly in India. Concerns about the potential impact that new seed-based technologies might have on rice genetic diversity and environmental sustainability have heightened farmers' and consumers' concerns about hybrids potentially replacing traditional landraces or high-yielding varieties that are currently cultivated by farmers and enjoyed by consumers. These concerns have been further exacerbated by campaigns that put a spotlight on the central role played by multinationals in the development and distribution of hybrid rice, drawing attention to a wide

[2] *As an example, in temperate Asian countries, such as Japan and China, sticky and soft rice is preferable. As such,* japonica *or* indica/japonica *hybrids, which have generally low amylose content, are preferable, because these will result in grains that become soft and sticky during cooking. In tropical South Asia, on the other hand, consumers prefer fluffier, nonsticky rice. Hybrids born out of any combination with low-amylose* japonica *varieties (like those imported or derived from parental lines imported from China) will tend to result in grains that become soft and sticky during cooking, which consumers in those countries may perceive as being of lower quality.*

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range of concerns including the theft or contamination of extant rice genetic resources; exploitative monopoly seed pricing and noncompetitive market practices; and an (inaccurate) conflation of hybrids with genetically modified organisms. While Kuyek (2000) presents many of these issues in an analytical manner, many other sources do not, making the socio-cultural discourse on hybrid rice murky (see, for example, GM Watch 2005).

Even if we assume that price signals do not reward farmers for the cultivation of hybrid rice, consider the fact that a significant portion of smallholder farmers in both India and Bangladesh meet their household (caloric) food security requirements with consumption of their own farm output. So how do they fare with hybrid rice? A recent study from Bangladesh drawing on the BIHS data described earlier suggests that own-consumption of hybrid rice constitutes a higher percentage of total rice consumption among poor households than rich households, implying that the impact of the low consumption qualities may be limited primarily to households with marketable surpluses (McFall, Magnan, and Spielman 2013).

This analysis opens the door for further consideration of the distributional aspects of hybrid rice adoption. Data from India suggest that most hybrid rice adopters tend to be relatively wealthy. Specifically, the CSISA baseline survey data indicate that nearly 75% of all hybrid rice adopters in the sample have incomes above the poverty line, and more than half of all adopters in the sample have per capita incomes that fall in the upper-middle or upper income quintiles. In addition, the proportion of households adopting hybrid rice increases with increasing income (table 3). Comparing adoption rates across adjacent quintiles indicates that there is generally a significant pattern of increased adoption rates with higher income. Although this correlation could be capturing a relationship between hybrid adoption and incomes (e.g., through increased rice productivity), there are strong theoretical grounds for inferring that wealth or income condition 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 technologies such as hybrids (e.g., Feder 1980; Feder, Just, and Zilberman 1985). Unfortunately, the underlying sampling frame of the CSISA baseline data limits our ability to explore these correlations further to test causal relationships or to draw any generalizable conclusions on these relationships.

Table 3 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* (0.438)
Middle 20%	22.64 (0.419)
Upper middle 20%	28.30** (0.451)
Richest 20%	34.34** (0.476)

Source: Authors, based on data from CSISA (2011).
*Notes: Standard deviations are provided in parentheses. Significance based on one-tail t-tests of group adoption rates among adjacent income groupings; * Significant at 5 percent level; ** Significant at 10 percent level.*

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Table 4 Hybrid Rice Adoption in Bangladesh, by Income Quintiles, 2011

Income Quintile	Adoption Rate (%)	$P(A_Q\text{-}A_{Q-1}) > t$
Poorest 20%	4.00 (0.196)	
Lower middle 20%	4.91 (0.216)	0.1508
Middle 20%	4.00 (0.196)	0.8492
Upper middle 20%	4.73 (0.212)	0.2020
Richest 20%	4.82 (0.214)	0.4602

Source: Authors, based on data from Ahmed et al. (2013).
Notes: Standard deviations are provided in parentheses. Significance tests are computed comparing adoption rates in one quintile to adjacent quintile (i.e., lower middle to poorest, middle to lower middle, and so on) based on one-tail t-tests. No statistical significance is found based on one-tail t-tests of group adoption rates among adjacent income groupings at the 1 percent, 5 percent, or 10 percent levels.

Our analysis of hybrid rice in Bangladesh explores this further. BIHS data suggest that farmers with larger landholdings are significantly more likely to adopt hybrid rice than farmers with either medium or small landholdings. BIHS data also suggest that households with per capita incomes greater than US$1.25 per day (adjusted for inflation and differences in purchasing power) are more likely to adopt hybrid rice (table 4). While this contrasts with findings from Azad et al. (2008), who find no discernible pattern in wealth and income determinants of hybrid rice adoption based on a panel of farmers surveyed during 2004–2006, this result could simply reflect the strong correlation between wealth or income and other important socioeconomic characteristics, such as access to credit, market information, or interactions with extension officers.

Several recent studies that investigate the underlying adoption determinants of hybrid rice in Bangladesh shed further light on these relationships. Using the same BIHS data described above, Ward and Pede (2015) estimate an adoption equation controlling for endogenous peer effects and contextual effects. Their results suggest that larger farmers and those with access to credit are more likely to adopt hybrids, and that adoption is actually independent of overall household wealth.

By combining sample survey and census data collected at the household and subdistrict (*upazilla*) levels by the Bangladesh Bureau of Statistics, Mottaleb, Mohanty, and Nelson (2014) estimate an adoption equation to explain what drives the likelihood and extent of hybrid rice adoption relative to traditional and modern rice varieties. Their findings suggest that access to credit, roads, irrigation, and seed dealers, as well as land characteristics (susceptibility to droughts, floods, and salinity) are key determinants of hybrid rice adoption. The studies by Mottaleb et al. (2014) and Ward and Pede (2015) therefore suggest an important role for policy reforms aimed at improving access to credit. As these results suggest, such policy reforms may result in an overall improvement in the equity of access to improved agricultural inputs such as rice hybrids, regardless of farmers' degree of wealth.

Policy and Investment Options for Hybrid Rice Innovation

The returns to hybrid rice cultivation and the distribution patterns of hybrid rice adoption suggest that the technology is still nascent. Despite some evidence of increasing adoption, it remains to be seen whether hybrid

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Table 5 Hybrid Rice Adoption in Bangladesh, by Landholding Classification, 2011

Landholding classification	Adoption Rate (%)	$P(A_L\text{-}A_{L-1}) > t$
Smallest 30% (avg. landholding 0.14 acres)	5.93 (0.236)	
Middle 40% (avg. landholding 0.47 acres)	7.79 (0.268)	0.0556
Largest 30% (avg. landholding 1.47 acres)	13.11 (0.338)	0.0001

Source: Authors, based on data from Ahmed et al. (2013).
Notes: Standard deviations are provided in parentheses. Significance tests are computed comparing group adoption rates to adjacent group (i.e., medium landholders to small landholders, large landholders to medium landholders) based on one-tail t-tests. The difference in adoption rates between small and medium landholders is significantly different from zero at the 10% level, while the difference in adoption rates between medium and large landholders is statistically significant at the 1% level.

rice will contribute to food security in line with the expectations of policy makers. Any expansion in this contribution will require closer consideration of several major issues: public investment in research, the small-country problem, intellectual property rights, competition versus innovation, and product delivery. We explore these issues here and provide explicit policy recommendations that can contribute to advancing hybrid technology.

Public Investment in Upstream Science

The first set of issues pertains to the technical issues surrounding hybrid rice. Without going into extensive technical detail, greater investment in research will be required to expand the narrow germplasm base from which hybrid rice research is being conducted, secure high and stable levels of heterosis, improve the consumption qualities of hybrid rice, and enhance the effectiveness of hybridization systems used to produce hybrid rice seed (Spielman et al. 2012). At present, the narrow genetic diversity of the existing stock of cytoplasmic male sterile (CMS) lines has resulted in the vulnerability of many hybrids to various pests.[3] Furthermore, most existing rice hybrids cultivated throughout South and Southeast Asia are not well adapted to the regions' tropical agroecological conditions, which has resulted in hybrids with limited yield advantages over modern inbred varieties (particularly compared with Chinese hybrids grown in more temperate conditions). Most scientists interviewed for this study agree that the current stock of scientific and technical knowledge is at a level at which many of these problems can be readily solved with sufficient time, effort, and resources. But given the time lag between research investment and product delivery, this also suggests that solutions will not be immediately available or remunerative in commercial markets.

As with most crop research—including other hybrid crops that are potentially lucrative in downstream markets—an optimal level of upstream

[3]*The primary challenge to producing heterosis in rice is that rice is a self-pollinating (inbred) crop. The plant contains small flowers with both male and female organs and is thus able to pollinate without separate parents. To produce heterosis from separate parents requires the use of three distinct lines of rice and is referred to as the three-line or CMS system. Specifically, the system requires a first cross between a male sterile plant (the A line, or maintainer line) with a genetically identical plant that is not sterile (the B line). The offspring of this plant is sterile. This offspring is then crossed with a genetically distinct plant (the R line, or restorer line) to create a new, fertile offspring (the F1 hybrid) that exhibits heterosis when planted. A later improvement on this three-line CMS system is the two-line system in which a male sterile line is crossed with the restorer line to produce F1 hybrids. See Li et al. (2010).*

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public investment is required to translate the science into a viable technology. Public investment in research 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. In addition, where neither private firms nor sovereign governments are willing to invest in removing these constraints—where the public good is global rather than country-specific in nature—there is a case for international public investment in research. In other words, hybrid rice research is not only a public good, but also a global public good, implying that market incentives result in underinvestment from both the private sector and from national governments, and thereby justifying a more global approach to public investment (Sandler 2002; Dalrymple 2006; Spielman 2007).

Arguably, hybrid rice research has 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 interviewed for this study that a large portion of the funding and scientific effort was allocated to capacity strengthening, demonstrations, and dissemination activities, all conducted around a limited set of hybrids and hybrid parental lines. These funding commitments overlooked the technical challenges mentioned above in favor of near-term outputs and likely impeded progress in solidifying the science underpinning hybrid rice for South Asia. This suggests the need for renewed and sustained public investment in hybrid rice science to address these unresolved technical challenges.

In this vein, several innovative strategies being formed around hybrid rice are worth noting. IRRI's HRDC has provided 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.

Another 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 CMS sources, molecular tagging and mapping, and the multiplication and distribution of IRRI germplasm.

These analytical observations all point to an overarching policy priority: greater public investment in upstream research on hybrid rice. Investments by national governments, bilateral and multilateral donors, and charitable

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foundations would keep organizations such as IRRI and national agricultural research systems engaged in upstream, collaborative hybrid rice research through mechanisms like the HRDC.

The Small-Country Problem

The second issue is the small-country problem that most relevant to Bangladesh. For small economies such as Bangladesh, where public research funding is limited and where few firms have the capacity to manage sufficiently large hybrid rice breeding programs, the importation of hybrid seed and parental lines for seed production may be a reasonable strategy. However, the strategy also means that these hybrids may be poorly adapted to Bangladesh's agroecological context, crop management practices, farming systems, and consumer preferences. One risk of this strategy arises from the volatile and sometimes unpredictable nature of trade policy: should Chinese exporters or Bangladeshi importers be unable to (or choose not to) ensure a continuous flow of germplasm from year to year due to tariffs, regulations, or other barriers imposed by either trading partner, the benefits of hybrid rice cultivation could dry up quickly. Although this is not a pressing concern for either country at the moment, China's reported unwillingness to share its more advanced breeding lines and systems with other countries suggests that such threats may be constantly looming on the horizon.

These observations suggest the need for high-level discussions on ways to strengthen global cooperation and accelerate the international movement of genetic materials that are essential to hybrid rice research—particularly the movement of parental lines from China to other developing countries. Cross-country transfers would require a significant increase in international and regional cooperation. As the world's premier rice research institute with a global mandate, IRRI plays a central role in this discussion, as does the FAO as the United Nations' lead organization on food and agriculture matters.

To this end, several advances have been made. First, Bangladesh and India (along with Nepal) have signed an agreement to harmonize seed certification processes between the two countries, paving the way for the more rapid release of improved rice varieties developed in either country (IRRI 2014; Singh and Jain 2014). While this agreement does not cover hybrid rice, it is an important symbolic move toward greater cross-border cooperation around product development and marketing that could encourage similar agreements for hybrid rice seed and segments of South Asia's seed market. Second, the FAO recently formalized a regional strategy for sustainable hybrid rice development in Asia that, as one of its key themes, promotes more extensive sharing of knowledge and materials between countries in the region. These are significant advances in terms of global and regional policy. However, greater leadership, vision, and cooperation involving both China and India—as well as the international donor community—remain necessary. From global efforts that began in the 1950s to combat crop diseases through breeding to recent global efforts to breed more nutritious crops, there is sufficient historical precedent for international cooperation of this level, type, and magnitude to suggest that solutions to the small-country problem are readily available.

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Seed Market Regulations and Intellectual Property Rights Protection

A third issue relates to the regulatory environment in which hybrid rice is developed and marketed—regulations that cover both the use of intellectual property embodied in hybrid rice seed and the markets in which the seed is exchanged between sellers and farmers. We explore each of these here.

In many industrialized countries, private investment in seed-based technologies is significantly determined by the existence of a credible IPR policy regime (see Naseem et al. 2010). Such regimes are not always present in developing countries or, if they exist, may be weakly enforced. Under such circumstances, breeders, seed companies, and entrepreneurs use hybrids as a biological form of IPR protection, since the expression of heterosis declines to such a degree in subsequent generations of seeds that farmers are generally compelled to procure new F1 seeds ever year. Private firms are likely to view biological IPR protections as an effective option, particularly where they are complemented 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 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 provide incentive for 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, few South Asian countries have sufficiently credible PVP laws. India's Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act of 2001 and the associated PPV&FR Authority provides the region's highest standard of protection, but Bangladesh lags behind in this regard.

Relatedly, many developing countries struggle with the design and enforcement of seed regulations that are meant to encourage rapid growth in the commercial end of the market in which firms with potentially valuable intellectual property operate. Both India and Bangladesh have made considerable progress in simplifying seed market regulation to allow firms to introduce new hybrids with minimal testing requirements. But ensuring that farmers have complete information about the quality of seed they purchase, the recommendations for use, and other necessary information to make best use of the technology remains a challenge.

These findings suggest the need for policy reforms and investments in capacity strengthening to improve seed market regulations in South Asia. Since information and capacity are rarely symmetric between seed providers and farmers in such situations, it is critical for these countries to develop outreach strategies that make the regulatory and legal system more accessible to farmers. For example, both countries would benefit from the introduction of point-of-sale monitoring by seed quality agencies to address farmers' concerns about seed quality. Similarly, both countries would do well to strengthen farmers' options for recourse in cases where harm has been demonstrated from the sale of low-quality or fraudulent seed. While the truthful seed-labeling regulations in both countries effectively allow hybrid rice seed to permeate local seed markets rapidly, few farmers have the requisite information or capacity to seek redress when seed quality issues affect their farm output. This implies that farmers (and companies) need to be better informed of their rights and responsibilities under the

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laws and regulations governing hybrid rice seed sales, marketing, and purchases.

Competition versus Innovation

An additional regulatory issue emerges around the issue of competition and industry concentration. In most South Asian countries, the formal rice seed market is largely concentrated around the high-volume, low-margin varietal end of the business and is not what might be termed cutting-edge in the seed industry. Only a few firms have entered the high-value segment of the market with hybrid rice seed. With such a small number of companies in the hybrid seed market, there are concerns that large companies operating in highly oligopolistic conditions will be able to exert a high degree of market power over farmers—including small-scale, resource-poor farmers. This concern is often voiced in India—even though the hybrid rice market there is host to a fairly sizeable contingent of seed companies—and in other countries, including Bangladesh, where the market is much thinner. 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. This is particularly relevant for India, which has agencies mandated to monitor antitrust activities.

Product Delivery

Finally, there is the issue of innovating around the delivery of hybrid rice to smallholder farmers in India and Bangladesh. As shown earlier, little is known about the size, depth, and heterogeneity of the hybrid rice market, or how farmers will respond to new hybrids in the pipeline. Early research cited has been pessimistic about the prospects for hybrid rice among smallholders in both countries, but signals from the private sector seem to indicate that significant resources are being allocated to marketing and distribution. Meanwhile, the governments of both India and Bangladesh have been keen to allocate public resources to subsidize hybrid rice seed and complementary inputs for farmers. Although subsidies have strong historical precedence in encouraging the adoption of new technologies in South Asia, such interventions may ultimately work against widespread adoption and the growth of a competitive hybrid rice seed industry. South Asia's experience with input subsidies suggests that 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. Other developing countries' experiences with input subsidies further suggest that such market interventions merely displace purchases that farmers would otherwise make (e.g., Ricker-Gilbert, Jayne, and Chirwa 2011). Taken together, the evidence suggests that there is little to be gained in the long term from hybrid rice seed subsidies. While further research is required to better understand the factors that motivate or constrain farmers' adoption of hybrid rice and the costs and benefits of subsidy schemes, it is unlikely that the short-term gains from such subsidies will result in long-term productivity gains. Understanding these factors will help not only inform future investments in product development but will also provide insight into alternative policy options that can accelerate the widespread adoption of hybrids.

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Conclusions

This article examines the innovation systems underlying hybrid rice in India and Bangladesh. It 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.

There is an immense stock of scientific knowledge and expertise on hybrid rice. Although much of this stock resides in China, high-quality expertise and accumulated experience also exist within the international agricultural research system, among multinational and domestic firms in the private sector, and in public research organizations in other Asian countries. More important, many of these actors are closely linked through a variety of scientific, professional, and product-related networks.

Several policy innovations could accelerate the discovery, development, and delivery of hybrid rice technology in Asia. First is greater public investment in the upstream research on hybrid rice to develop the tools and technologies needed to advance the technology. International and national funding for public research that addresses 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. 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.

A second set of policy innovations revolve around stronger incentives designed to attract private investment into hybrid rice development. Already, the private sector has signaled a willingness to invest substantially in the technology. Public policy could be directed toward promoting an enabling environment that provides the appropriate incentives for increased private investment, including more effective regulation of the seed markets in which hybrid rice seed is distributed, and stronger enforcement of IPR policies that protect innovators who invest in hybrid rice development. In addition, public policy could facilitate the transfer of genetic materials within (e.g., from the public sector to the private sector) and across country borders. Greater exploration of regional research consortium approaches such as the HRDC that involve private sector partners, public-private research partnerships, and regional harmonization of seed market regulation are potentially valuable means of combining the distinct strengths of the two sectors.

A third set of policy innovations relate to public intervention in the markets through which hybrid rice technologies are delivered. Careful thought needs to be given to the use of public resources to subsidize hybrid rice seed and complementary inputs. Although the short-term gains in rice production and adoption trajectories—alongside the political gains of subsidies—may be significant, the long-term potential for elite capture, displacement effects, and subsidies-in-perpetuity are nontrivial.

In summary, although hybrid rice has the potential to change the face of rice cultivation in India and Bangladesh, it has yet to reach a threshold point. Establishment 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. In turn, these outcomes

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could improve food security and allow for the reallocation of land and other resources to higher-value agricultural and nonagricultural activities. However, the innovation process is far from complete. Significant scientific, technical, and policy challenges exist at each stage—discovery, development, and delivery—and repeated iterations of research and development need to be pursued. The ability of public policy makers, corporate decision makers, scientists, entrepreneurs, and farmers to understand these challenges and anticipate solutions is fundamental to the long-term success of hybrid rice in South Asia.

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