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Application of Frontier Technologies for Agricultural Development*

Pratap S. Birthal†

I

BACKGROUND

During the past five decades, technological changes in agriculture and allied sectors backed by massive investment in irrigation, infrastructure and institutions have propelled many food-insecure, import-dependent developing countries, including India, into food self-sufficiency. The adoption of biochemical and mechanical technologies in India have led to near-tripling of foodgrain production and four-fold increase in production of fruits and vegetables during the period 1966-67 to 2011-12. There has also been an unprecedented increase (6-10 times) in the production of animal food products during this period. Milk production has increased six-fold, egg production 12-fold and aquaculture production 8-fold. The burgeoning population, which is likely to reach 1.5 billion by 2030, however, keeps the challenge of producing more food as significant as in the past. Besides, the demographic transformation, urbanisation and sustained growth in income are causing a change in the dietary pattern, away from staple cereals towards high-value commodities like vegetables, fruits, milk, meat, eggs and fish. It is projected that by 2030 India will require a minimum of 304 million tonnes of foodgrains, 175 million tonnes of vegetables, 96 million tonnes of fruits, 170 million tonnes of milk and 21 million tonnes of meat, eggs and fish (Joshi and Kumar, 2011).

Balancing the growing food demand with domestic production is unlikely to be as smooth as in the past. Agricultural production systems will come under the confluence of biotic and abiotic stresses. Land will emerge a strong limiting factor to food and agricultural production. India's net cropped area almost stagnates at around 140 million hectares; and the scope to increase food and agricultural production through area expansion is limited. According to an estimate, about 120 million hectares of land in the country suffers from one or the other form of degradation (NAAS, 2010 cited in Singh 2011). Water is a critical input in agriculture, which uses over 80 per cent of the available water. Groundwater in the intensively-cultivated northwestern food basket of the country has already reached its limits of exploitation

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†National Centre for Agricultural Economics and Policy Research, New Delhi 110 012. The author acknowledges the intellectual input received from Shiv Kumar, P.K. Joshi and Ramesh Chand while preparing this paper.

(Government of India, 2011a). The agricultural production will become more energy-intensive but with a concomitant shift from the use of renewable to fast-exhausting non-renewable sources, (Jha *et al*., 2012). Intensification of agriculture will further strain these natural resources. Increasing competition for land, water and energy will intensify due to their pressing demands for housing and industrialisation; and thus there is a high probability of their diversion away from agriculture. These challenges will be aggravated further by increasing frequency of extreme climatic events, such as droughts, floods, cyclones, heat waves, etc.

Technology has been the key driver of agricultural growth in the past. Its growth effects, however, have started diminishing of late. Growth in total factor productivity, as also in yields of most crops and livestock species, have decelerated considerably in recent years (Chand *et al*., 2011). For instance, yield of rice and wheat that had grown at a rate of 2.4 per cent and 2.9 per cent per year, respectively during the last quarter of the twentieth century, decelerated to 1.4 per cent and 0.8 per cent in the first decade of the twenty-first century--a clear evidence of decline in the contribution of technology to agricultural growth. This is a matter of serious concern. Slow growth in agriculture will adversely impact farm incomes, food security, and even growth of non-farm sector which has strong backward and forward linkages with agriculture.

In view of these challenges, the future growth in agriculture has to come from acceleration in the rate of technological change and sustainable intensification of the production systems. This paper examines the potential of some of the frontier technologies related to breeding of crops and animals, and natural resources management in improving food and nutritional security, and enhancing agricultural growth and rural development. It addresses two important issues that have considerable potential to influence agricultural growth and rural development. First, it discusses the extent to which agricultural productivity can be improved using the existing knowledge and technologies. This includes bridging of yield gaps and using of resource conservation technologies. Second, it explores the potential of frontier sciences like biotechnology, nanotechnology, remote sensing and information technologies in raising the yield frontiers.

II

BRIDGING THE YIELD GAPS

Yield gap is the difference between realised yield and potential yield; the potential yield being the yield obtained under “an idealised state in which a crop grows without any biophysical limitation other than uncontrollable factors, such as solar radiation, air temperature, and rainfall in the rain-fed systems” (Lobell *et al*., 2009). Yield potential is measured as the yield obtained from the experiments designed to eliminate all yield-reducing factors or the simulated yield assuming a perfect growing environment, except uncontrollable factors. Estimating a perfect yield potential is rather difficult because of the imperfections in management of the factors determining the yield.

In India, the average yield obtained from front-line demonstrations on farmers' fields is a commonly used indicator of yield potential for practical and policy purposes. Available evidence indicates that there exist significant differences in realised and obtainable yields of most crops both within and across the states which cannot be explained by the local physical conditions (Table 1). Yield gaps are generally large for rainfed crops and less-developed states. In the rainfed regions, realised yields of most crops are around 50 per cent of their potential yields (Aggarwal *et al*., 2008). In the irrigated regions, for example in Punjab and Haryana, the yield potential, to a large extent, has been exploited. Note that yield gaps cannot be fully exploited. The realised yield of any crop hardly exceeds 80 per cent of its potential yield, as the marginal cost of producing additional output beyond this level generally out weighs the incremental benefits due to additional yield (Pingali and Rajaram, 1999).

Yield gaps exist because of a number of technical and economic reasons. The lack of access to technical knowledge, quality inputs, information, services and credit may restrict utilisation of existing knowledge and technologies. Higher risks in production and prices may prevent the farmers from adoption of yield-enhancing technologies and management practices. Lack of incentives, poor infrastructure and under-developed institutions raise transaction costs, which act as important barriers to adoption of improved technologies and to long-term investment in land and water management. Sometimes, the cost of inputs and prices of outputs may not be rational to increase productivity. Nevertheless, if farmers are facilitated to overcome some of these constraints, there is a substantial potential to increase agricultural production by promoting better use of the existing knowledge and technologies. It may be noted that bridging of yield gaps may cause degradation of natural resources (soil degradation and over-extraction of groundwater) and environment.

III

HARNESSING THE POTENTIAL OF RESOURCE CONSERVATION TECHNOLOGIES

The natural resource base of agriculture is becoming increasingly stressed. Land and water, the two most important factors of production, are scarce, and these are deteriorating fast quantitatively as well as qualitatively due to intensification of agriculture and their increasing demand in non-agricultural uses. Conservation of land and water resources and their efficient use, therefore, are critical in enhancing and sustaining productivity of agriculture.

Water Harvesting

India has about 1900 billion cubic metres of water available from internal renewable resources, of which 1030 billion cubic metres can be potentially utilised

TABLE 1. YIELD GAPS IN WHEAT AND RICE IN SELECTED STATES OF INDIA- 2003-05

(*tonnes/ha*)

	Irrigated wheat			Irrigated rice			Rainfed rice (upland)		
State (1)	Improved practices (2)	Farmers' demonstrations (3)	State average (4)	Improved practices (5)	Farmers' demonstrations (6)	State average (7)	Improved practices (8)	Farmers' demonstrations (9)	State average (10)
Punjab	4.46	4.03	4.20	8.25	7.85	5.28			
Haryana	4.75	4.52	3.96	7.11	6.78	4.82			
Rajasthan	3.94	3.72	2.79						
Uttar Pradesh	4.20	3.32	2.79	7.05	5.20	2.18	3.62	2.48	1.94
Gujarat	4.04	3.49	2.68	5.58	4.89	1.89			
Madhya Pradesh	3.29	2.47	1.78						
Bihar	3.65	2.90	1.78	4.88	4.15	1.51			
Maharashtra	3.41	2.90	1.33						
Jharkhand							2.29	1.38	1.69
Chhattisgarh				3.91	3.13	1.45	3.74	3.13	1.45

Source: Government of India (2011b).

for human and other uses as against the current utilisation of 761 billion cubic metres. More than half of India's cultivated land is rainfed; and a sizable proportion of it can be provided with irrigation water if it were possible to harvest rainwater. From a water balance analysis of 225 predominantly rainfed districts in the country, Sharma *et al.* (2010) have reported the possibility of harvesting a surplus run-off of 114 billion cubic metres from 28.5 million hectares of the cropped land. In a normal monsoon year, with 28 billion cubic metres of the harvested water it is possible to provide a supplementary irrigation of 100 mm to 25 million hectares of land. While in a drought year, assuming that the run-off surplus is reduced to half of the normal level, a supplementary irrigation of 100 mm can irrigate 20.6 million hectares.

The potential benefits of rainwater harvesting are enormous, especially during the years of deficit rainfall (Table 2). A supplementary irrigation with traditional cropping practices can generate additional crop output of 12 per cent, while with application of improved cropping practices this may go up to 45 per cent. The monetary value of the additional output in normal monsoon year is estimated to be sufficient to recover the investment made in the development of water harvesting systems. The pay-offs, however, are larger with the application of improved technologies. From the meta-analysis of investment on watershed programmes, Joshi *et al.* (2008) have reported an internal rate of return of 27.4 per cent. These findings suggest that there is an immense scope to improve agricultural production using the available potential rainwater; but this can be operationalised only with enhanced investments and institutional interventions.

TABLE 2. BENEFITS AND COSTS OF WATER HARVESTING IN RAINFED AREAS IN INDIA

	Traditional technology		Improved technology	
Particulars	Normal monsoon	Drought season	Normal monsoon	Drought season
(1)	(2)	(3)	(4)	(5)
	Change in production over normal production (per cent)			
Rice	15.81	16.75	46.62	49.61
Coarse cereals	10.31	7.83	53.13	41.14
Oilseeds	12.37	11.03	39.35	37.74
Pulses	12.48	11.71	30.99	29.00
	Annualised cost and benefits (Rs. billion)			
Cost		50.91		
Gross benefits	49.36	44.71	145.31	132.34
Net benefits	-1.55	-6.20	94.40	81.43

Source: Sharma *et al.* (2010).

Micro-Irrigation

The pressurised irrigation systems, such as sprinkler and drip irrigation systems, possess considerable potential to improve water use efficiency and enhance agricultural productivity in water scarce areas. These technological improvements in the methods of irrigation also reduce water losses, enhance input-use efficiency, reduce energy consumption, control soil erosion and reduce biotic stresses such as pest and weed infestations. Evidence indicates that as compared to the traditional method of irrigation, viz., flooding, application of drip irrigation technology in horticultural crops saves water by 12-84 per cent, reduces energy consumption by 29-45 per cent and improves crop yields by 7-98 per cent (Narayanamoorthy, 2003; Narayanamoorthy, undated). Drip irrigation technology is considered more profitable in wider-spaced horticultural crops; but it also generates substantial benefits in crops like cotton, groundnut and sugarcane. Water saving and yield benefits of sprinkler irrigation are also highly attractive. Sprinkler irrigation in foodgrain crops can save water to the extent of 40 per cent, and improve yields up to 20 per cent. In oilseed crops too, these benefits are reported to be around 30 per cent.

The pay-offs from investment on micro-irrigation technologies are quite high. Drip irrigation has been found to generate additional income in the range of 22 to 83 per cent (Narayanamoorthy, 2003; Suresh Kumar and Palanisami, 2010). Malik and Luhach (2002) have estimated the internal rate of return to be 33 to 47 per cent and Palanisami *et al*., (2011) 5 to 410 per cent on the investment in drip irrigation. Similarly, the internal rate of return on investment in sprinkler irrigation has been reported to be in the range of 3 to 115 per cent (Palanisami *et al*., 2011).

Despite high pay-offs, area under micro-irrigation has not exceeded 4 million hectares or 4.5 per cent of the gross irrigated area in the country, as against the potential of 42 million hectares (Palanisami *et al*., 2011). Of the total micro-irrigation potential, 70 per cent is suitable for sprinkler technology and 30 per cent for drip technology. There is a considerable variation in the exploitation of micro-irrigation potential across the states. Andhra Pradesh, Chhattisgarh, Karnataka, Maharashtra, Tamil Nadu and Haryana are the leading states in the adoption of micro-irrigation technologies, where 22-51 per cent of the available micro-irrigation potential has been exploited as compared to the national average of 9.5 per cent. In other states, their potential has remained almost unexploited. Uttar Pradesh, Madhya Pradesh, Rajasthan, Gujarat and Punjab together share 70 per cent of the micro-irrigation potential in the country, but these have hardly exploited 5 per cent of it. The main reasons for non-adoption of micro-irrigation technologies include higher initial capital requirement, poor quality of equipment and accessories and lack of knowledge in operation and maintenance of the system (Shah and Keller, 2002; Namara *et al*., 2005; Palanisami *et al*., 2011).

Micro-irrigation did not receive much policy attention in the past. Of the total area under micro-irrigation, 90 per cent was developed between 2005 and 2010, mainly due to implementation of a central government scheme on micro-irrigation. This is an important finding and suggests the need for an incentive structure for farmers and also for manufacturers of micro-irrigation equipment. The 12th Five-Year Plan targets bringing 10.1 million hectares under micro-irrigation-- 4.8 million hectares under drip irrigation and 5.3 million hectares under sprinkler irrigation. It is worth mentioning that as compared to that in many developed and developing countries, micro-irrigation in India is grossly under-developed. Globally, 20 per cent of the irrigated area is through micro-irrigation systems - 58 per cent in the Europe, 44 per cent in the Oceania and Pacific, 40 per cent in the Americas and 22 per cent in the Africa (Kulkarni *et al*., 2006).

Laser Land Leveling

Laser land leveling is another water-saving technology, usually appropriate for regions with uneven fields where a considerable amount of irrigation water is lost due to extensive application of flooding method of irrigation. Unevenness of fields reduces input-use efficiency and creates larger biotic and abiotic pressures on crop growth, which ultimately reduce yield potential and add to the cost of production. Several field studies conducted in the Indo-Gangetic Plains, where flooding is a common method of irrigation, have brought out that laser leveling technology could save irrigation water by 10-30 per cent, improve fertiliser-use efficiency by 6-7 per cent and enhance crop yield by 3-19 per cent, besides expanding cropped area by 3-6 per cent (Jat *et al*., 2006; Sidhu *et al*., 2010; Kaur *et al*., 2012; Jackson, 2009). An *ex-ante* assessment of the potential benefits from the adoption of laser leveling technology on 2 million hectares in the Indo-Gangetic Plains has indicated a saving of 1.5 million hectare-metres of irrigation water and 200 million litres of diesel, besides additional revenue of US$500 million from yield improvements (Jat *et al*., 2006). Adoption of laser leveling, however, is constrained by higher initial investments on machines and equipment, non-availability of skilled labour to operate machines, dominance of smallholdings, lack of collective action and policy focus.

Zero or Reduced Tillage

Zero tillage, also known as zero till, no till, direct seeding and direct drilling, has been reported as one of the most successful resource conservation technologies in the Indo-Gangetic Plains (Erenstein *et al*., 2007). In 2003-04, a total of 820 thousand hectares of wheat area was tilled using this technology. Most of it, however, was confined to Haryana (46 per cent), Punjab (26 per cent) and western Uttar Pradesh (21 per cent). Adoption of zero/reduced tillage has started picking up in eastern Uttar Pradesh and Bihar.

Zero tillage generate substantial environmental and economic benefits--around 80 per cent saving in tractor-time, 60-80 per cent in fuel consumption and 20-35 per cent in irrigation water (Erenstein and Laxmi, 2008). Other benefits of zero tillage include improvements in soil organic carbon content and reduction in weed pressure. In regions where sowing of wheat is delayed due to late planting of rice, its yield is affected due to terminal drought. Zero tillage enables timely sowing of wheat on residual moisture after rice harvest and helps wheat crop escape terminal drought. Yield or income gains due to zero tillage are quite reasonable. It improves wheat yield by 15.4 per cent (9.4 per cent due to timeliness in sowing and 6.0 per cent due to improved input-use efficiency) (Mehla *et al*., 2000). Lack of access to information about technology, high initial capital investment on machinery and equipment and dominance of smallholdings are important constraints to the adoption of zero tillage.

The potential economic and environmental benefits of conservation technologies are clear and compelling. These need to be expropriated through appropriate incentives (e.g., subsidies on machinery) and institutional arrangements (e.g., co-operatives for custom-hiring of machinery). Remote sensing and geographic information system (GIS) can aid in the management of natural resources by allowing monitoring of land and water resources, and in predicting extreme climatic events like droughts and floods. By combining data on soils, topography and rainfall, it is possible through GIS to evolve suitable crop plans suitable for different agro-ecologies. Other important applications of GIS include crop forecast, pest and disease surveillance and monitoring of weather dynamics.

IV

RAISING THE YIELD FRONTIERS THROUGH APPLICATION OF FRONTIER SCIENCES

Enhancing agricultural production in the long-run would require application of frontier sciences for breeding of crops and animals. Modern sciences such as biotechnology, nanotechnology, remote sensing, and information and communication technology (ICT) offer opportunities to enhance genetic potential of crops, improve input-use efficiency, reduce production and transaction costs and improve sustainability of natural resources.

Biotechnology

Biotechnology allows selective genetic modifications of flora and fauna at the genetic molecular level. In crop breeding, modern biotechnology has two main advantages over the traditional breeding methods. One, it provides a means to precisely select the gene for a particular trait; and two, it allows transfer of gene for a particular trait across species using techniques, such as genetic engineering, genomics, micro-propagation, tissue culture and marker-assisted breeding.

There is considerable accumulated evidence that suggests that biotechnology possesses enough potential to transform agriculture and agri-food industry and to contribute to human welfare. The main application of biotechnology is in developing seeds that provide higher yields at a lower cost and/or to offer resistance to biotic and abiotic stresses, such as droughts, floods, heat waves, frosts, insects, weeds, etc. The other important applications of modern biotechnology include transfer of gene with nitrogen fixing capacity onto cereals and bio-fortification of crops for improving human health and nutrition. Biotechnological research has taken rapid strides towards achieving these objectives.

Though not a product of modern biotechnology the hybrid rice technology has succeeded in enhancing rice production from limited land and in improving food security in many developing countries. For example in China the first rice hybrid was released in 1976, and since then rice production and yield in the country have increased substantially. Between 1976 and 2010, rice yield almost doubled, from 3.5 tonnes per hectare to 6.5 tonnes per hectare; and rice production went up from 129 million tonnes to 197 million tonnes. The hybrid rice cultivation has now spread to over two-thirds of the total rice area in China. With such a huge yield advantage, China could meet its rice demand from 7 million hectares less land than in 1976.[1] On the contrary, hybrid rice technology has not made any significant headway in India. Presently, only about 2.5 million hectares land is under hybrid rice cultivation, largely concentrated in the eastern India, (Viraktamath *et al.*, 2010) as against the estimated potential of 10 million hectares.

Through modern biotechnology many crops have been genetically modified to provide solution for a specific input trait. Crops such as cotton, soybean, canola, maize, papaya, potato, sugar beets and alfalfa are have been genetically modified for management of insect pests and weeds. Transgenics of these crops are now available for commercial cultivation across the world. In 2011, biotech crops occupied 160 million hectares of land across the globe, and half of it was in developing countries (James, 2011). United States with a share of 43.1 per cent, is the leading biotech country, followed by Brazil (18.9 per cent), Argentina (14.8 per cent), India (6.6 per cent) and China (6.5 per cent). It may be noted that in the US, Brazil, Argentina and Canada genetically modified maize, soybean, canola and sugarbeet occupy around 90 per cent of the area under their cultivation.

By averting yield loss, improving yields, reducing use of agro-chemicals and enhancing input-use efficiency, the genetic modification for an input trait directly benefits the farmers. The genetic modification for an output trait (e.g., nutrition, therapeutics) directly benefits the consumers. Beta-carotene fortified rice, called ‘Golden Rice’, is an example. There is considerable scope for commercial cultivation of ‘Golden Rice’ in the countries suffering from beta-carotene deficiency-induced diseases. In Bangladesh and Philippines, the Golden Rice is in its initial stage of commercialisation. In India, rice lines with varying levels of beta-carotene are ready for field trials. High-starch potatoes, that absorb less fat when fried, are now being commercially cultivated in the United States.

According to an estimate, between 1996 and 2010 the biotech crops added US$78 billion to the global economy by way of improved yields and reduced input costs (Brookes and Barfoot, 2012). Their cultivation could reduce pressure on land and conserve biodiversity. During this period, by cultivating biotech crops the world produced an additional 276 million tonnes of food, feed and fibre. In the absence biotech crops, the world would have required an additional 91 million hectares of land to produce this amount with the use of conventional technologies. Further, by reducing pesticide-use by 443 million kg (active ingredient), biotech crops also reduced environmental footprints of agriculture. Biotech crops could also mitigate some of the challenges of climate change. In 2010 alone cultivation of biotech crops could save over 19 billion kg of CO_2 through reduced use of fuels (for spraying of pesticides) and conservation tillage.

Bt cotton is the only genetically modified crop being cultivated in India, primarily to manage yield loss due to a deadly pest *Helicoverpaarmigera* that has developed resistance to most insecticides applied to control it. Bt cotton was introduced in India in 2002, and since then its area has increased exponentially to occupy close to 90 per cent of the total cotton area in 2011 (Figure 1). Adoption of Bt cotton has transformed India's cotton economy, with a 3.5-fold increase in cotton production and a substantial rise in exports from 0.05 million bales in 2001-02 to 8.3 million bales in 2009-10.

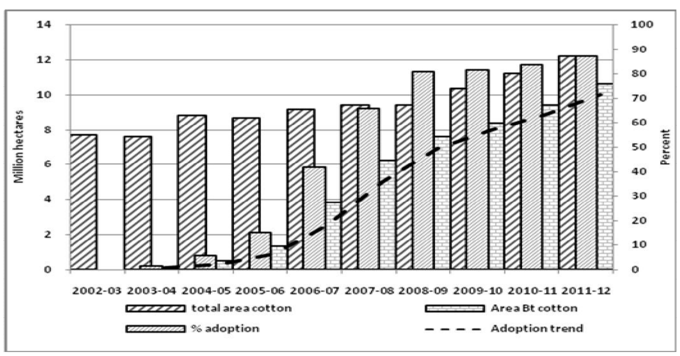


Figure 1. Trend in Adoption of Bt Cotton in India

Farmers in rainfed areas have benefitted immensely from the technological transformation of cotton production system. A number of field studies conducted in India have confirmed the economic and environmental benefits of cultivation of Bt cotton (Bennett *et al.*, 2006; Gandhi and Namboodiri, 2006; Qaim, 2006; Sadashivappa and Qaim, 2009; Subramanian and Qaim, 2009, 2010; Krishna and Qaim, 2012). Most of these studies report a minimum 30 per cent yield gain, 40 per cent reduction in insecticide-usage and 50 per cent more farm income. Aggregate economic benefits from adoption of Bt cotton are huge. During 2002-2010, Bt cotton generated additional income of US$ 9.4 billion (Table 3). Besides, the spread of Bt cotton has also indirectly benefitted the local economy, in terms of increased employment and income opportunities in the non-farm business and trading activities. Each dollar of direct benefits is estimated to generate indirect benefits worth US$ 0.8 (Subramanian and Qaim, 2009; 2010). Bt cotton has also impacted poverty reduction as the poor share about 60 per cent of the gains due to adoption of Bt cotton. It may be noted that *Helicoverpaarmigera* is a polyphagus pest surviving on many food and non-food crops. Its control through Bt gene in cotton is likely to have reduced damages for other crops on which it feeds.

TABLE 3. GAINS FROM ADOPTION OF BT COTTON IN INDIA, 2002-2010

Year (1)	Cost change (US$/ha) (2)	Net increase in gross margins (US$/ha) (3)	Increase in farm income (US$ million) (4)
2002	-12.4	82.7	3.7
2003	-16.2	209.9	21.0
2004	-13.6	193.4	96.7
2005	-22.3	256.0	332.7
2006	3.5	221.0	839.9
2007	26.4	356.9	2094.0
2008	24.3	256.7	1790.2
2009	22.2	211.2	1755.0
2010	23.1	265.8	2498.5

Source: Brookes and Barfoot (2012).

Bt brinjal is the first genetically modified food crop developed in India with the intent to provide a solution against fruit and shoot borer. Evidence indicates that cultivation of Bt brinjal can reduce insecticide-use by 42-77 per cent and enhance yield by 37-55 per cent (Krishna and Qaim, 2008; Kumar *et al*., 2010). However, its higher seed price increases the cost of cultivation by 8-30 per cent (Krishna and Qaim, 2008). Nonetheless, the higher seed cost is well compensated by the increased yield - the net margins from cultivation of Bt brinjal are estimated to be 60-180 per cent more than those from the common varieties and hybrids of brinjal. Assuming a conservative yield gain of 33 per cent and unit cost reduction of 17 per cent, Kumar *et al*. (2010) have reported that adoption of Bt brinjal on 30 per cent of the total brinjal area would generate a surplus of Rs 11.7 billion per annum. A larger share of the benefits, however, is likely to accrue to consumers.

Brinjal cultivation is concentrated in the agriculturally and economically laggard eastern region of the country. The consumers and producers of this region will therefore benefit more from technological improvements in brinjal cultivation. The eastern region is poverty-ridden; and adoption of Bt brinjal is likely to benefit millions of poor consumers as well producers there. Bt brinjal was recommended for commercial release in 2009 but has been put on temporary hold because of concerns from some quarters regarding its environmental and health effects.

Yield enhancement will remain the main focus of the conventional as well as modern biotechnology research; the need to develop crop strains that are water and energy-efficient cannot be undermined. Returns to investment on stress-tolerant breeding are expected to be quite attractive. A 5-10 per cent higher crop yield and an internal rate of return of 29-167 per cent on investment in drought-tolerant rice research have been reported for eastern India (Pray *et al*., 2011; Gautam, 2009; Mottaleb *et al.,* 2012). An *ex-ante* assessment of the benefits of drought-tolerant wheat and maize (Kostandini, 2008) and groundnut (Birthal *et al*., 2012) research has brought out that adoption of drought-tolerant varieties can considerably reduce production risks. Rice cultivars (e.g., Subarna Sub 1) that can withstand prolonged sub-emergence are now becoming popular. Research on improving photosynthesis through genetic modification is in progress. The C_4 crops, such as maize and sugarcane, are more efficient in the conversion of solar energy, and this trait can be utilised in other crops following biotechnological approaches.

The current focus of biotechnological research in India is to develop crop varieties and hybrids with higher and stable yields. There is considerable emphasis on developing rice varieties that can offer resistance to multiple biotic and abiotic stresses (James, 2010). Research on breeding for delayed ripening traits in fruits and vegetables is also underway. Presently, there are 11 crops (brinjal, cotton, groundnut, mustard, papaya, potato, rice, sorghum, sugarcane, tomato and watermelon) that are in the process of genetic modification at the public sector research institutions, and 8 crops (brinjal, cabbage, cauliflower, cotton, maize, okra, rice and tomato) at the private sector institutions (James, 2010).

Biotechnology also contributes towards improving the quality of natural resources. Microbial biotechnology based products, viz., bio-fertilisers and bio-pesticides improve soil health and preserve environment. These are being commercially produced in India. Besides, micro-organisms are also being utilised for bio-degradation of agricultural and household wastes, and reclamation of degraded soils.

Livestock constitute an important component of Indian agriculture, generating agricultural growth, improving nutritional security and reducing rural poverty (Birthal and Negi, 2012). A number of technologies - both conventional and modern - that have potential to improve animal productivity are available for commercial use. Artificial insemination is one such technology, which is widely used in animal reproduction for breeding quality animals. Sexed semen technology offers a choice to livestock farmers between calf and heifer, depending on their relative economic utility, and is available for commercialisation in the country. Some advanced breeding technologies such as embryo transfer and marker-assisted selection have been perfected but not transferred to the farmers because of their being capital and knowledge-intensive (Madan 2005; Nimbkar and Kandasamy, 2011). Genetically modified cows producing milk with higher level of casein protein, have been developed in New Zealand (Ruane and Sonnino, 2011). Research on reducing lactose-content of milk to make it suitable for milk-lactose in-tolerant populations is under way. Fermentation and microbial technologies (e.g., probiotics) are being adopted to improve quality and digestibility of feeds and fodders. Likewise, vaccines have been widely used to control animal diseases. Biotechnological tools are also being used for disease diagnosis and food preservation.

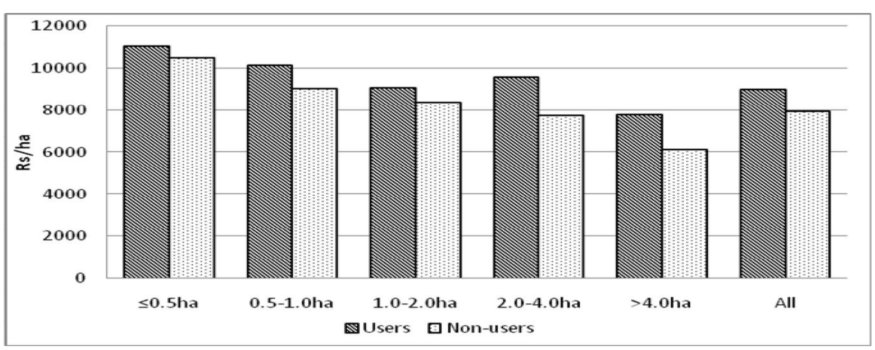
Nanotechnology

Nanotechnology is emerging as an important tool to bring precision in agriculture and agri-food industry. Its potential applications in crop production include controlled release of pesticides, stabilisation of bio-pesticides, slow release of nano-material assisted fertilisers, bio-fertilisers and micronutrients for efficient use; and nano-material assisted delivery of genetic material for crop improvement (Ghormade *et al*., 2011). Nanosensors can be used for detecting plant pathogens and pesticides, and for soil conservation and remediation. This way the nanotechnology can improve input-use efficiency, reduce input losses and assist in development of precision farming. Nanotechnology can also help protecting environment through use of alternative (renewable) energy supplies, and filters or catalysts to reduce pollution and clean up the existing pollutants. The potential applications of nanotechnology in food industry include packaging, storage and processing of food commodities for improved quality, safety and shelf-life (Kalpna Sastry *et al*., 2011), especially of perishable commodities that suffer heavy post-harvest losses.

Information and Communication Technology (ICT)

Given that the future increases in food production must come from exploitation of biological potential and efficient use of natural resources, agriculture is likely to become more complex, and knowledge-intensive. Farmers will demand varied types of information to take rational decisions in respect of choice of crops, inputs, technologies, markets, etc. as to improve productivity and maximise profit, and to comply with market preferences for diverse, safe and quality food whilst preserving the natural resources. To adjust to these changes and remain competitive in the market, the farmers need a variety of information on a continuum from plough to plate.

There is evidence that use of information in decision-making enhances farm income by about 13 per cent per hectare (Figure 2). However, the information is not accessible to all the households and is often biased against the smallholders. Only about 40 per cent farm households in India gather information from one or another source, but mainly from informal sources including progressive farmers and input dealers. The outreach of the public extension worker has remained limited to about 6 per cent of the households (Government of India, 2005).



Source: Extracted from Government of India (2005).

Figure 2. Net Returns for Users and Non-Users of Agricultural Information

Information and communication technologies (ICT) offer an unique opportunity to obtain an easy access to information on agricultural technologies, inputs, weather, markets, prices, etc. Several studies have shown that access to information via telephones, mobile phones and internet reduces costs associated with information search significantly and helps farmers obtain higher yields, reduce risks and realise better prices for their produce (Jenson, 2007; Aker, 2010; Goyal, 2010; Mittal *et al*., 2010, Ali, 2012).

IV

CONCLUSIONS AND IMPLICATIONS

Modern biotechnology is not a panacea for all the problems that farmers face. But, its application along with the conventional technologies can make significant contributions towards improving agricultural productivity and food and nutritional security; and promoting sustainable use of natural resources. India has made significant progress in frontier sciences including biotechnology, remote sensing, geographic information system, and ICT; their potential has remained under-exploited so far due to a number of policy and non-policy factors. In order to operationalise the growth potential of modern as well as conventional technologies, there is a need to prioritise efforts and investments on a continuum, and create a level playing field for generation and dissemination of agricultural research through appropriate policies and institutions.

In short-to-medium run, research and development efforts should focus on bridging the yield gaps that continue to be very large in most crops, especially in the rainfed environments. Technologies, such as zero tillage, laser land leveling and micro-irrigation have enough potential to save water and energy, reduce cost of production and improve crop yields. Reducing the yield gap will necessarily require investments in soil and water management, and development of institutions for delivery of improved technologies, inputs, information and services. Besides, there is a need for crop planning taking into consideration the heterogeneity in resource endowments and infrastructure across the regions. Remote sensing and GIS offer great opportunity do this. Besides, these technologies can be gainfully utilised to alert farmers about uncertain phenomena of weather conditions and of pest outbreak and infestation, and to enhance resilience of agricultural production systems. Information and communication technologies will complement these efforts, and contribute towards making agriculture more remunerative by bringing down the costs associated with search of information.

Growth in agriculture in the long-run has to come necessarily from technological breakthroughs at the genetic molecular level as to push the yield frontiers upward and to enhance the resource-use efficiency and in a manner that is environment-friendly, economically-viable and socially-acceptable. Despite their significant potential to contribute towards improving food, nutritional and livelihood security; the public acceptance of biotech crops/products has been limited because of their speculated risks to human health and environment. The debate has become polarised both 'for and against'. It may be noted that genetically modified foods are not intrinsically bad or good. For instance, foods with more beta-carotene will benefit populations suffering from night blindness. However, the genetic modification by way of inter-species gene transfer may cause allergic reactions to human beings and animals. Likewise, the spread of insect-resistant biotech crops may induce secondary pest outbreak and pest resurgence, and suppression of activities of the beneficial insects. No such problems, however, have been scientifically reported in major biotech crop growing countries, like US, Brazil and Argentina, and even in the countries that import genetically modified food and non-food commodities. In India, Bt cotton is being cultivated for over a decade, and nothing adverse has been reported despite its multiple usage as fibre, feed and food. It may be noted that India also imports large quantities of soybean oil from countries like Argentina, Brazil and US where genetically modified soybean occupies close to 90 per cent of the total soybean area.

In India, about 100 research institutions and 140 private companies are engaged in transgenic research on 35 crops targeting 18 traits (Rao, 2012). Thus, several genetically modified crops are expected to be available for commercial cultivation in the near future. However, given the polarisation of debate on biotech crops, there is a need for (i) a rigorous scientific assessment of the perceived benefits and risks of genetic modification to human health and environment, (ii) evolving food safety and biosafety regulations for the entire supply/value chain taking into consideration the international standards and agreements, (iii) generating public awareness about the advantages and disadvantages, myths and realities of the genetically modified crops, and (iv) developing a system of labeling to ensure the traceability of the genetically modified products for information of the consumers.

India has established a Biotechnology Regulatory Authority that will supersede and undertake functions of the earlier committees related to (i) recommendation and creation of guidelines (Recombinant DNA Advisory Committee), (ii) adherence of standards of safety in R&D (Institutional Biosafety Committees), (iii) field trials and safety upon release (Review Committee on Genetic Manipulation), (iv) commercial application (Genetic Engineering Approval Committee), and (v) monitoring and performance of genetically modified crops (State Biosafety Coordination Committees and District Level Committees).

There is a considerable dualism in biotechnology research and the available biodiversity across the world. While most of the biotechnology research is being conducted in developed countries, developing countries are rich in biodiversity and *vice versa*. There is apprehension of bio-piracy or exploitation of the biodiversity or natural resources of the developing countries. However, this bio-prospecting of the biodiversity opens avenues for developing countries to benefit from the product development process through royalty sharing mechanism.

Much of the research in agricultural biotechnology is conducted by the private sector, where the processes and products are legally protected by the Intellectual Property Rights. This means there could be monopoly or near-monopoly of the private sector on the processes and products of biotechnology. This has implications for the public research system, seed business and farming community. The public sector institutions may be denied access to basic proprietary knowledge and processes of research, as the protection of the biotech products involves substantial cost, which the private sector generally recovers from the seed industry and farmers.

Another related concern is the suitability of the type of crop and the trait for which it is modified through genetic engineering to the social and cultural environment of the developing countries. As biotechnology research is concentrated in developed countries, research institutions in there often target crops and traits that are suited to their agro-climatic and social environments; and these may not be adaptable to the conditions of the developing countries. Further, when the motive is rent-seeking, the private sector may not engage in research on crops/traits that benefit the poor because of low returns on the investments in research in these crops. This calls for a need to target biotechnology research on commodities and traits that are important to the livelihood of the poor and are cultivated in the marginal environments.

Modern agricultural biotechnology improves yields, enhances resistance to pests and tolerance to extreme climatic events, and can be useful for the poor in enhancing their income and food security. Small land holders dominate Indian agriculture; and it is apprehended that they may be bypassed by the biotechnology revolution because of their lack of access to costly biotech products and inputs. Such a dualism in technology adoption has been noticed in the case of Bt cotton when small farmers could not adopt it because of higher seed cost. However, with seed market becoming competitive the rent-seeking started disappearing, lowering seed costs. Moreover, increase in production cost is well compensated by yield increase. Most biotech products are scale-neutral; and with appropriate technological, institutional and policy support, the small farmers can harness their potential to enhance their income and livelihood status.

There are multiple approaches to enhance food and agricultural production, and research agenda should include all the facets of science and technology that have potential to make an impact on social welfare. New technologies including transgenic crops and animals should not be discriminated against *a priori* on the ethical or moral grounds or precautionary principles, and the potential cost of not accepting new technologies must be taken into consideration in the science policy decisions.

NOTE

1. In 2010, China allocated 30.1 million hectares under rice as compared to 37.0 million hectares in 1976.

REFERENCES

Aggarwal, P.K., K.B. Hebbar, M.V. Venugopalan, S. Rani, A. Bala, A. Biswal and S.P. Wani (2008), *Quantification of Yield Gaps in Rain-fed Rice, Wheat, Cotton and Mustard in India*, Global Theme on Agroecosystems Report No. 43, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, (Andhra Pradesh).

Aker, J.C. (2010), *Dial "A" for Agriculture: Using Information and Communication Technologies for Agricultural Extension in Developing Countries,* Memio, Tufts University.

Ali, J. (2012), "Factors Affecting the Adoption of Information and Communication Technologies for Farming Decisions", *Journal of Agricultural and Food Information*, Vol. 13, No. 1, pp. 78-96.

Bennett, R., U. Kambhampati, S. Morse and Y. Ismael (2006),"Farm-Level Economic Performance of Genetically Modified Cotton in Maharashtra, India", *Review of Agricultural Economics*, Vol. 28,No.3, pp.59–71.

Birthal, P.S. and D.S. Negi (2012), "Livestock for Higher, Sustainable and Inclusive Agricultural Growth", *Economic and Political Weekly,* Vol. 47, Nos.26-27, June 30, pp. 89-99.

Birthal, P.S., S.N. Nigam, V. Narayanan and A. Kareem (2012), "Potential Economic Benefits from Adoption of Improved Drought-Tolerant Groundnut in India," *Agricultural Economics Research Review*, Vol. 25, No.1. January-June, pp.1-14.

Brookes G. and P. Barfoot (2012), *GM Crops: Global Socio-Economic and Environmental Impacts 1996-2010*.P.G. Economics Ltd, Dorchester, UK.www.pgeconomics.co.uk/.../2010-global-gm-crop-impact-studyfinal-April-2010.pdf.

Chand, R., P. Kumar and S. Kumar(2011), *Total Factor Productivity and Contribution of Research Investment to Agricultural Growth in India*, Policy Paper 25, National Centre for Agricultural Economics and Policy Research, New Delhi.

Erenstein, O. and V. Laxmi (2008), "Zero Tillage Impacts in India's Rice–Wheat Systems: A Review", *Soil and Tillage Research*, Vol.100, pp.1-14.

Erenstein, O., R.K. Malik and S. Singh (2007), *Adoption and Impacts of Zero Tillage in the Irrigated Rice–Wheat Systems of Haryana, India,* Research Report, CIMMYT India and Rice Wheat Consortium, New Delhi.

Gandhi, V. and N.V. Namboodiri (2006), *The Adoption and Economics of Bt Cotton in India*, Working Paper No. 2006-09-04, Indian Institute of Management, Ahmedabad.

Gautam, A. (2009), *Impact Evaluation of Drought Tolerant Rice Technologies through Participatory Approaches in Eastern India*. Masters' Dissertation, The State University of New Jersey, Rutgers.

Ghormade, V., M. V. Deshpande and K. M. Paknikar (2011), "Perspectives for Nano-Biotechnology Enabled Protection and Nutrition of Plants", *Biotechnology Advances,* Vol. 29, pp. 792-803.

Government of India (2005), *Situation Assessment Survey of Farmers,* National Sample Survey Organisation, Ministry of Statistics and Programme Implementation, New Delhi.

Government of India (2011a), *Ground Water Year Book – India*, Central Ground Water Board, Ministry of Water Resources, Faridabad.

Government of India (2011b), *Challenges of Food Security and Its Management,* National Rainfed Area Authority, Planning Commission, New Delhi.

Goyal, A. (2010), "Information, Direct Access to Farmers, and Rural Market Performance in Central India", *American Economic Journal Applied Economics*, Vol 2, pp. 22-45.

Jackson, M.T. (2009), *Revitalising the Rice-Wheat Cropping Systems of the Indo-Gangetic Plains: Adaptation and Adoption of Resource-Conserving Technologies in India, Bangladesh, and Nepal*, International Rice Research Institute, Las Banos, Philippines.

James, C. (2010), *Global Status of Commercialized Biotech/GM Crops: 2010,* ISAAA Brief No. 42, International Service for the Acquisition of Agri-biotech Applications, Ithaca, New York.

James, C. (2011), *Global Status of Commercialised Biotech/GM Crops: 2011,* ISAAA Brief No. 43, International Service for the Acquisition of Agri-biotech Applications, Ithaca, New York.

Jat, M.L.; P. Chandna; R.K. Gupta, S.K. Sharma and M.A. Gill (2006), *Laser Land Leveling: A Precursor Technology for Resource Conservation*, Technical Bulletin Series 7, CIMMYT India and Rice Wheat Consortium, New Delhi.

Jensen, R. (2007), "The Digital Divide: Information (Technology), Market Performance and Welfare in the South Indian Fisheries Sector", *Quarterly Journal of Economics*, Vol. 127, No. 3, pp. 879-924.

Jha, G.K., Suresh Pal and Alka Singh (2012), "Changing Energy-Use Pattern and the Demand Projection for Indian agriculture", *Agricultural Economics Research Review*, Vol. 25, No. 1, pp.61-68.

Joshi, P.K.; A.K. Jha; S.P. Wani; T.K. Sreedevi and F.A. Shaheen (2008), *Impact of Watershed Program and Conditions for Success: A Meta-Analysis Approach*, Global Theme on Agroecosystems Report No. 46, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh.

Joshi, P.K. and P. Kumar (2011), *Food Demand and Supply Projections for India*, International Food Policy Research Institute, New Delhi (unpublished).

Kalpna Sastry, R., H.B. Rasmi and N.H. Rao (2011), "Nanotechnology for Enhancing Food Security in India", *Food Policy*, Vol. 36, No.3.

Kaur, B., S. Singh, B.R. Garg, J.M. Singh and J. Singh (2012), "Enhancing Water Productivity Through On-farm Resource Conservation Technology in Punjab Agriculture", *Agricultural Economics Research Review*, Vol. 25, No.1, January-June 2012, pp. 79-85.

Kostandini, G. (2008), *Three Essays on Measuring the Ex-ante Economic Impacts of Agriculture Technology Innovations*, Doctoral Dissertation, Virginia Polytechnic Institute and State University, Virginia.

Krishna, V.V. and M. Qaim (2008), "Potential impacts of Bt Eggplant on Economic Surplus and Farmers' Health in India", *Agricultural Economics*, Vol. 38, No. 2, pp. 167–180.

Krishna, V.V. and M. Qaim (2012), "Bt Cotton and Sustainability of Pesticide Reduction in India', *Agricultural System,* Vol. 107, pp. 47-55.

Kulkarni, S.A., F.B. Reinders and F. Ligetevari (2006), Global Scenario of Sprinkler and Micro Irrigated Areas, Paper Presented at the 7th *International Micro Irrigation Congress*, Kuala Lumpur, September 10-16.

Kumar, S., P.A.L. Prasanna and S. Wankhade (2010), *Economic Benefits of Bt Brinjal- An Ex-ante Assessment*, Policy Brief No. 34, National Centre for Agricultural Economics and Policy Research, New Delhi.

Lobell, D.B., K.G. Cassman and C.B. Field (2009), "Crop Yield Gaps: Their Importance, Magnitudes and Causes", *Annual Review of Environment and Resources*, Vol. 34, No.10, p. 1146.

Madan, M.L. (2005), "Animal Biotechnology: Applications and Economic Implications in Developing Countries", *Rev. Sci. Tech. Off. Int. Epiz.* Vol. 24, No. 1, pp. 127-139.

Malik, D.P. and M.S. Luhach (2002), "Economic Dimensions of Drip Irrigation in Context of Fruit Crops", paper presented at *International Workshop on Economics of Water and Agriculture* held at Institute of Food, Agriculture and Environmental Sciences, The Hebrew University, Jerusalem, Rehovot, Israel, December 18-20.

Mehla, R.S., J.K. Verma, R.K. Gupta and P.R. Hobbs (2000), *Stagnation in the Productivity of Wheat in the Indo-Gangetic Plains: Zero-Till-Seed-cum-Fertiliser Drill as an Integrated Solution*, Rice–Wheat Consortium Paper Series 8. CIMMYT India and Rice Wheat Consortium, New Delhi.

Mittal, S., S. Gandhi and G. Tripathi (2010), *Socioeconomic Impact of Mobile Phones on Indian Agriculture*, Working Paper No. 246, Indian Council for Research on International Economic Relations, New Delhi.

Mottaleb, K.A., M. Roderick, S. Mohanty, M.V.R. Murty, Tao Li, H. G. Valera and M.K. Gumma (2012), *Ex-ante* Impact Assessment of a Drought Tolerant Rice Variety in the Presence of Climate Change, Paper presented at the *Agricultural and Applied Economics Association Annual Meeting*, Seattle, Washington, U.S.A., August 12-14.

Namara, R. E., B. Upadhyay and R.K. Nagar (2005), *Adoption and Impacts of Micro-Irrigation Technologies: Empirical Results from Selected Localities of Maharashtra and Gujarat States of India*, Research Report 93, International Water Management Institute, Colombo, Sri Lanka.

Narayanamoorthy, A. (2003), "Averting Water Crisis by Drip Method of Irrigation: A Study of Two Water-Intensive Crops", *Indian Journal of Agricultural Economics*, Vol. 58, No. 3, July-September, pp. 427-437.

Narayanamoorthy, A. (undated), *Potential for Drip and Sprinkler Irrigation in India*, Gokhale Institute for Politics and Economics, Pune.

Nimbkar, C. and N. Kandasamy (2011), "Animal Breeding in India – A Time for Reflection and Action", *Journal of Animal Breeding and Genetics*, Vol. 128, pp. 161–162.

Palanisami, K., K. Mohan, K.R. Kakumanu and S. Raman (2011), "Spread and Economics of Micro-Irrigation in India: Evidence from Nine States", *Economic and Political Weekly*, Vol. 46, No. 26/27, June 25, pp. 81-86.

Pingali, P.L. and S. Rajaram (1999), "Global Wheat Research in a Changing World: Options and Sustaining Growth in Wheat Productivity", in P.L. Pingali (Ed.) (1999), *World Wheat Facts and Trends*, CIMMYT, Mexico.

Pray, C., L. Nagarajan, L. Li, J. Huang, R. Hu, K.N. Selvaraj, O. Napasintuwong and R. Chandra Babu (2011), "Potential Impact of Biotechnology on Adaption of Agriculture to Climate Change: The Case of Drought Tolerant Rice Breeding in Asia", *Sustainability*, Vol. 3, pp. 1723-1741.

Qaim, M. (2006), "Adoption of Bt Cotton and Impact Variability: Insights from India", *Review of Agricultural Economics*, Vol. 28, pp. 48-58.

Qaim, M., A. Subramanian and P. Sadashivappa (2009), "Commercialised GM Crops and Yield Correspondence", *Nature Biotechnology*, Vol. 27, No.9.

Rao, S.R. (2012), "Development of Genetically Engineered Crops – Public Policy, Regulatory Framework and Scientific Risk Assessment: Imperatives for Commercial Use", paper presented at *International Conference on Plant Biotechnology for Food Security: New Frontiers*, New Delhi, February 21-24.

Ruane, J. and A. Sonnino (2011), "Agricultural Biotechnologies in Developing Countries and Their Possible Contribution to Food Security", *Journal of Biotechnology*, Vol. 156, pp. 356-363.

Sadashivappa, P. and M. Qaim (2009), "Bt Cotton in India: Development of Benefits and the Role of Government Seed Price Interventions", *AgBioForum*, Vol. 12, No. 2, pp. 1-12.

Shah, T. and J. Keller (2002), "Micro-Irrigation and the Poor: A Marketing Challenge in Smallholder Irrigation Development", in Hilmy Sally and Charles L. Abernethy *Private Irrigation in Sub-Saharan Africa*, (Eds.) (2002), International Water Management Institute, Colombo.

Sharma, B.R., K.V. Rao, K.P.R. Vittal, Y.S. Ramakrishna and U. Amarasinghe (2010), "Estimating the Potential of Rainfed Agriculture in India: Prospects for Water Productivity Improvements", *Agricultural Water Management*, Vol. 97, pp. 23-30.

Sidhu, R.S., K. Vatta, and H.S. Dhaliwal (2010), "Conservation agriculture in Punjab – Economic Implications of Technologies and Practices", *Indian Journal of Agricultural Economics*, Vol. 65, No.3, July-September, pp. 413-427.

Singh, R.B. (2011), *Towards an Evergreen Revolution- The Road Map*, National Academy of Agricultural Sciences, New Delhi.

Subramanian, A. and M. Qaim (2009), "Village-wide Effects of Agricultural Biotechnology: The Case of Bt Cotton in India", *World Development*, Vol. 37, No.1, pp. 256–267.

Subramanian, A. and M. Qaim (2010), "The Impact of Bt Cotton on Poor Households in Rural India", *Journal of Development Studies*, Vol.46, No.2, pp. 295-311.

Suresh Kumar, D. and K. Palanisami (2010), "Impact of Drip Irrigation on Farming System: Evidence from Southern India", *Agricultural Economics Research Review*, Vol. 23, No. 2, July-December 2010, pp. 265-272.

Viraktamath, B.C., A.H. Prasad, M. Ramesha and M.I. Ahmed (2010), *Hybrid Rice in India: Current Status and Future Prospects*, Directorate of Rice Research, Hyderabad.