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Review Paper

Evidences from agronomic innovations shaping sustainable agriculture in India

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ABSTRACT

Indian agriculture continues to confront persistent challenges arising from low resource-use efficiency, substantial yield gaps, declining farm profitability, and escalating environmental stress, compounded by climate variability and growing food demand. While genetic improvement has driven productivity gains historically, the transformative role of agronomic innovations in enhancing system efficiency and sustainability remains comparatively under-documented. This study synthesizes major agronomic technologies mainly from director of Agronomy ICAR-IARI, with the objective of quantifying their contributions to productivity, profitability, resource-use efficiency, and environmental sustainability. The scope encompasses critical irrigation scheduling (e.g., crown root initiation stage in wheat), conservation agriculture and integrated crop management, integrated farming systems, subsurface drip fertigation, precision nutrient management including neem-coated and nano-urea-based strategies, and advanced weed management solutions addressing herbicide resistance and zero-till systems. Evidence indicates that these technologies have generated substantial and scalable impacts, including yield gains of 10–30% in major cereals, water and nitrogen savings of 25–40%, significant reductions in greenhouse gas emissions, and large economic benefits of several hundred crores annually at the national scale. Beyond productivity enhancement, these innovations have strengthened climate resilience, improved soil health, and reduced input dependency, underscoring agronomy's central role in sustainable intensification. There may be several other success stories across the country, generated by different institutions and State Agricultural Universities, which remain unreported and therefore need proper documentation. This status paper is expected to serve as an icebreaker for systematic and scientific reporting of the real-field impact of agronomic interventions.

***Key words*:** Agronomic innovations; Conservation agriculture; Integrated farming systems; Impact assessment; Resource-use efficiency; Precision nutrient management

At present, the biggest challenge facing Indian agriculture is poor resource-use efficiency (RUE), large yield gaps across crops and regions, declining profitability, rising input costs, increasing stress on production systems, hidden unemployment, and a growing environmental footprint. Although India possesses only about 2.5% of the world's land resources and 4% of global freshwater resources, it has to support more than 17% of the world's human population along with a very large livestock population of the second largest in the world after Brazil (>12%) (Anonymous 2023). Further, the poor RUE in Indian agriculture is reflected in low water and nutrient conversion into crop output, with the sector consuming about 80% of the country's water resources yet achieving only around 35–40% water use efficiency, meaning much of the water applied does not translate into productive crop biomass (Rathore *et al.,* 2015), and widely used surface irrigation, contributing to over-exploitation of groundwater and unreliable irrigation coverage (~51% of agricultural area); similarly, nitrogen fertilizer use efficiency in India's major cropping systems hovers at roughly 30–40%, leading to economic losses and nutrient leaching into water bodies (Padhan *et al.,* 2021). These inefficiencies stem from conventional practices such as flood irrigation, broadcast fertilization, poor timing and placement of inputs, and limited use of precision technologies. Improved agronomy through balanced nutrient management, micro-irrigation (drip/sprinkler) that can save 40–60% water and increase productivity by ~40–50%, crop diversification, (Rathore *et al.,* 2015, 2019, 2020) optimized sowing times, and conservation agriculture enhances RUE by ensuring inputs are

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applied at the right time, place and amount, reducing waste, increasing yields, and making farming more sustainable and climate-resilient (Padhan *et al.,* 2023). This imbalance makes it imperative to address the multiple leakages, inefficiencies, and emerging second-generation challenges in the farm production system.

Poor resource management lies at the core of many of the challenges confronting Indian agriculture and acts as a major driver of several interlinked problems. India faces a dual concern of limited natural resources and low efficiency in their utilization, which poses a serious threat to the long-term sustainability of its agricultural systems. At the same time, India has entered the category of a water-stressed nation based on per capita freshwater availability, yet the efficiency of water use in agriculture remains among the lowest, often below 30% for most crops. This is largely due to outdated and inefficient irrigation methods such as flood and check basin systems, along with other redundant and unimproved resource-use practices. Although a wide range of improved agronomic technologies and best management practices have been developed and demonstrated to significantly enhance productivity, resource use efficiency, and farmers' income, their adoption and scaling remain inadequate, limiting their overall impact. To address all these challenges need upscaling the improved agronomy.

Agriculture is both a contributor to and a victim of climate change, and inefficient use of natural resources is further exacerbating its environmental footprint. Therefore, it is imperative to identify and promote management practices that are environmentally sustainable. Several climate-resilient practices have been developed and upscaled over large areas, demonstrating remarkable potential in reducing stress and minimizing negative impacts on the soil–plant–animal–atmosphere continuum. A wide range of such innovations have been recommended to make Indian agriculture more climate-resilient and future-ready. In this paper, an attempt has been made to (i) enlist and categorize major agronomic innovations across key thematic domains and (ii) assess their quantified impacts on productivity, profitability, resource-use efficiency, and environmental sustainability. Accordingly, this paper synthesizes evidence on selected scalable agronomic innovations to assess their impacts on productivity, resilience, and sustainability, while inviting constructive feedback to further strengthen the framework for future evaluations.

Major Agronomic Technology Domains and Innovations

Irrigation and Water Management Technologies

Crown root initiation (CRI) stage–Based Irrigation Scheduling

During green revolution, the high yielding varieties of cereal resulted in quantum jump when fully supported by good agronomic practices to provide best possible environment to these plant types. The dwarf cultivar developed that time were responded very well to applied inputs especially irrigation and nutrients. A group of agronomists from the Division of Agronomy, ICAR-IARI led by Dr RBL Bhardwaj, (Bhardwaj, 1975) investigated the critical stages of wheat (Fig. 1) irrigation and identified crown root initiation (CRI) as a key stage for optimizing crop performance. Irrigation at the CRI stage was found to significantly influence the number of effective tillers, yield components, and final grain yield. Multiple studies were analyzed to quantify the contribution of CRI-stage irrigation, while Bhardwaj (1975) first highlight its importance for irrigation scheduling in dwarf wheat varieties. In India, wheat is cultivated over approximately 32 million hectares, with an annual production of 112 million tonnes. Irrigation at the CRI stage is widely practiced under both fully irrigated and rainfed (life-saving) conditions. Depending on soil type,

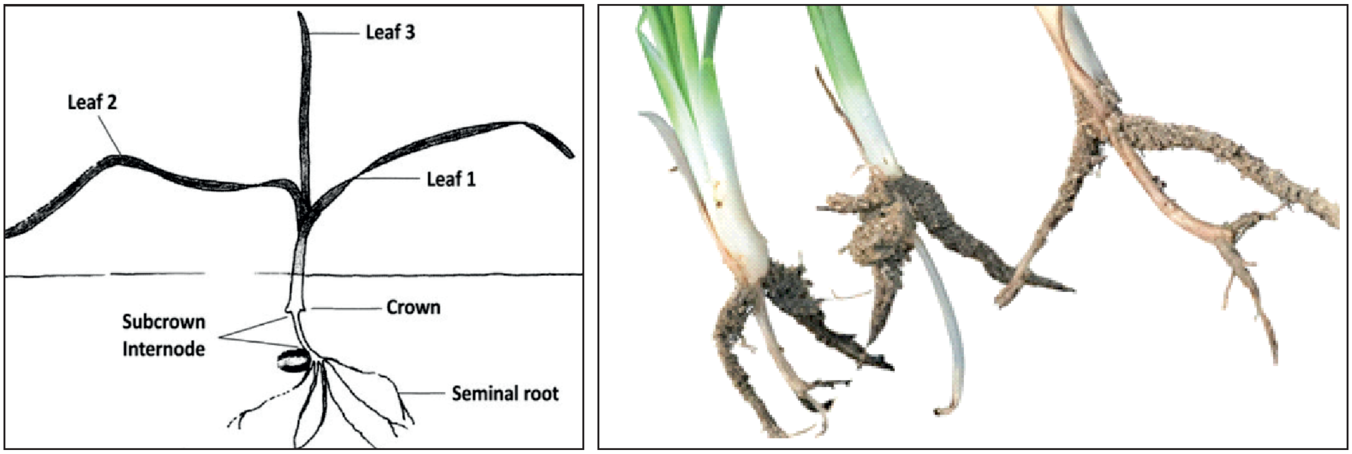

Fig 1. Crown roots in dwarf wheat

variety, and climatic conditions, irrigation at this stage contributes 20–30% of the final grain yield (Bhardwaj, 1975), equating to an additional 22.4–33.6 million tonnes of wheat. This translates to a gross economic benefit of ₹54,320–81,480 crore, underscoring the critical role of CRI-stage irrigation in sustaining wheat productivity in India.

Sub-Surface Drip Fertigation Systems

The Sub-surface Drip Fertigation System (SSDF) demonstrates strong potential to enhance productivity, profitability, and resource-use efficiency in maize–wheat systems. Evidence indicates that even with a 25% reduction in nutrient input, SSDF can increase maize and wheat yields by 15.3% and 10.4%, respectively, translating into an additional 5.5 Mt of maize and 11.34 Mt of wheat and generating economic gains of about ₹38,015 crore. Under full nutrient application, yield gains rise further (17.5% in maize and 15.4% in wheat), resulting in an additional 25.16 Mt of combined production and total additional returns of ₹58,274 crore. These results highlight SSDF as a scalable (Table 1 and Fig. 2), climate-smart, and economically viable technology that can simultaneously boost national food production, enhance farmer incomes, and reduce fertilizer-related environmental footprints. Strategic policy support for large-scale adoption of SSDF can therefore contribute significantly to sustainable agricultural intensification and long-term food security (Singh *et al.,* 2024, 2026).

The Sub-surface Drip Fertigation System (SSDF) offers a transformative pathway for achieving India's goals under the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), climate-resilient agriculture, and the vision of Viksit Bharat @2047. Empirical evidence shows that SSDF can enhance maize and wheat yields by 10–15% even with 25% nutrient savings, and by 15–18% under full fertigation, resulting in substantial gains in national food production and farm incomes. SSDF demonstrates its potential to improve water and nutrient use efficiency, reduce input wastage, and lower environmental footprints. By promoting precise input delivery, minimizing losses, and improving crop resilience to climate variability, SSDF aligns strongly with India's priorities of "Per Drop More Crop," sustainable intensification, and resource conservation. Targeted policy support, financial incentives, and integration of SSDF into national irrigation and climate-smart agriculture programs can accelerate its adoption and contribute significantly to long-term food security, farmer prosperity, and environmental sustainability.

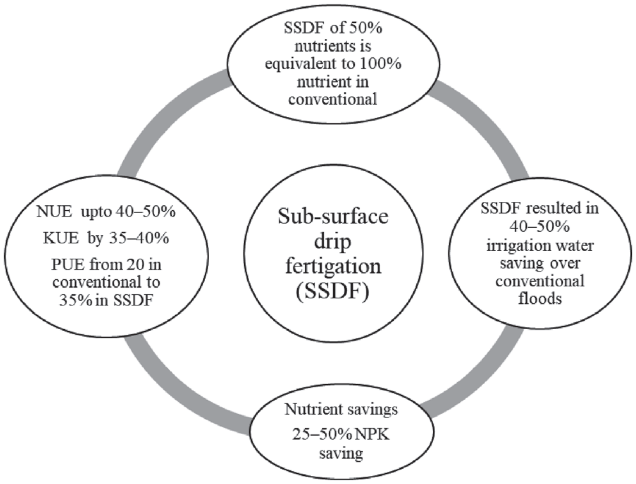

Fig. 2. Sub surface drip fertigation in cereal based system under CA and its impact

Nutrient Management and Fertilizer Use Efficiency

Efficient nutrient management, particularly nitrogen (N), constitutes a central pillar of agronomic innovation. Given that N fertilizers underpin India's food production but are characterized by low recovery efficiency (30–40%) and high economic and environmental costs, IARI-led interventions have focused on improving synchronization between crop demand and nutrient supply. These innovations have delivered substantial gains in N-use efficiency (NUE), productivity, and national fiscal savings, while

Table 1. Impact of SSDF in enhancing crop productivity, nutrient savings and generating additional income in niche area

S No.	Particulars	Maize	Wheat	Additional expected return both in maize and wheat crops
1	Area (mha)	10.9	31.8	
2	Average yield (t/ha)	3.3	3.43	
3	Total production (mt)	36	109.1	
4	Yield increase with 25% nutrient saving (%)	15.3	10.4	
5	Yield increase without nutrient saving	17.5	15.4	
6	Projected production under 25% nutrient saving	41.5	120.4	
7	Projected production without nutrient saving	44.33	125.87	
8	Additional production with 25% nutrient saving	5.5	11.34	
	Without nutrient saving	8.36	16.8	
	Additional returns (Crore Rs)	13208	25807	39015
	Additional returns (Crore Rs) without nutrient saving	20060	38214	58274

simultaneously reducing environmental externalities.

Neem-Coated Urea

Dr Rajendar Prasad and his team during eighties have developed protocols for increasing nitrogen use efficiency through coating of urea with neem oil (Bains *et al.,* 1971). It increases the recovery efficiency of applied nitrogen by reducing the N losses. The nationwide adoption of neem-coated urea represents a major policy success in improving nitrogen-use efficiency while reducing India's dependence on fertilizer imports (Prasad *et al.,* 1993, 1999, Shivay *et al.,* 2001). By slowing nitrification and minimizing nitrogen losses through volatilization and leaching, this innovation enables savings of about 5 kg urea/bag (~8%/ha) and nearly 7 kg nitrogen/ha, while improving nutrient-use efficiency by 10–15%. As a result, urea imports declined by nearly 7 million tonnes in 2023–24, generating substantial fiscal savings of 6,000–7,000 crore annually. Beyond economic gains, neem-coated urea enhances crop productivity and reduces environmental footprints, contributing to sustainable intensification of Indian agriculture. This intervention aligns strongly with national priorities of Atmanirbhar Bharat, climate-smart farming, and the Viksit Bharat @2047 vision by simultaneously improving farm profitability, resource efficiency, and macroeconomic stability.

Integrated Use of Nano-Fertilizers with Conventional Fertilizers

The global food system continues to rely heavily on conventional chemical fertilizers to sustain crop productivity in the post-Green Revolution era, despite shrinking arable land and mounting environmental pressures. Nitrogen fertilizers, especially urea, remain the backbone of global nutrient supply, with demand escalating sharply from 148.6 million metric tonnes (MMT) in 2009 (International Fertilizer Association, 2010) to nearly 199.7 MMT by 2024 (International Fertilizer Association, 2025), representing an increase of about 34.6% over the 2009 level. While this expansion has supported food security, it has also intensified environmental externalities associated with prilled urea production and field application, including more greenhouse gas emissions (515 kg CO_2 eq/tonne urea production), undue water (12.8 m^3/tonne of urea production) and energy (173.7 kWh/tonne of urea production) consumption, and low NUE (Upadhyay *et al.,* 2023a). These inefficiencies translate into substantial nitrogen losses through leaching and gaseous pathways, aggravating environmental pollution and undermining the sustainability of intensive agricultural systems.

In this context, the integration of nano-fertilizers particularly nano-urea with conventional urea represents a transformative agronomic strategy rather than a complete substitution. Nano-urea, characterized by its high surface area, controlled nutrient release, and enhanced leaf absorption efficiency, enables crops to meet nitrogen demand with substantially lower fertilizer inputs. When strategically combined with reduced doses of conventional urea, nano-urea improves nitrogen synchronization with crop demand, thereby minimizing losses and enhancing nutrient use efficiency. This integrated approach aligns productivity goals with environmental stewardship, offering a practical pathway to rationalize nitrogen inputs without compromising yield stability.

Evidence from intensive cereal- and oilseed-based cropping systems strongly supports the agronomic and environmental advantages of this integration (Table 2). Field experiments in maize-wheat and pearl millet-mustard systems

Table 2. Optimizing agronomy for use of nano fertilizers

Treatments	N Dose (kg/ha)	Urea Eq. (kg/ha)	Nano-urea application /ha (ml)	GHG emission (kg CO_2-eq/ha from urea)	GHG emission (kg CO_2-eq/ha nano-urea)	Total GHG emission (kg CO_2-eq/ha)	Reduction in GHG emission (kg CO_2-eq/ha) due to nano-urea application
Maize							
N_{100}PK	150	326	-	1,678.9	-	1,678.9	-
N_{75}PK+ Nano-urea	112.5	245	2500	1,261.8	0.62	1,262.4	416.5
Wheat							
N_{100}PK	120	261	-	1,344.2	-	1,344.2	-
N_{75}PK+ Nano-urea	90	196	2500	1,009.40	0.62	1,010.0	334.1
Pearl millet							
N_{100}PK	60	130	-	669.5	-	669.5	-
N_{75}PK+ Nano-urea	45	98	2500	504.7	0.62	505.3	164.2
Mustard							
N_{100}PK	80	174	-	896.1	-	896.1	-
N_{75}PK+ Nano-urea	60	130	2500	669.5	0.62	670.1	226.0

(Upadhyay *et al.,* 2023a)

demonstrate that replacing 25% of conventional nitrogen with nano-urea through foliar application sustains yields while significantly reducing nitrogen load (Upadhyay *et al.,* 2023a, 2023b; Singh *et al.,* 2026). Beyond yield performance, the synergistic application of nano-urea with conventional fertilizers exerts a positive influence on soil biological health. Shifts in microbial community composition toward beneficial taxa such as Actinobacteriota, Proteobacteria, and Bacteroidia further strengthen nutrient cycling and soil resilience (Upadhyay *et al.,* 2025). Importantly, these biological improvements reinforcing the agronomic viability of integrated nano-conventional fertilization strategies.

The cumulative global implications of nitrogen dose curtailment through nano-urea integration are substantial. At prevailing market prices, a 25% reduction in conventional urea use worldwide could save nearly 50 MMT annually, translating into economic benefits exceeding USD 19 billion per year. In India alone, such reduction could conserve nearly 9 MMT of urea, yielding enormous fiscal savings under both subsidized and market pricing scenarios. More critically, lower urea consumption directly reduces emissions associated with fertilizer manufacture and field-level nitrous oxide losses. A 25% substitution of conventional urea with nano-fertilizers could mitigate approximately 236 Mt CO-equivalent emissions annually, representing a significant contribution to global climate change mitigation efforts.

Further, India's annual urea consumption is 35.78 million metric tonnes (MMT) as per FAI 2023-24. A 25% reduction in usage through nano urea application could save approximately 8.945 MMT of conventional urea. With subsidized urea priced at INR 265/45 kg bag (equivalent to INR 588.89/100 kg or INR 5,888.89/tonne), the total savings would be 8.945 MMT × ₹5,888.89 = INR 52,650 crore annually. At the unsubsidized market price of INR 3,238 per 100 kg (INR ₹32,380/tonne), total potential savings based on full-cost pricing would be 8.945 MMT × 32,380 = INR 2,89,720 crore. Thus, the implementation of nano urea technology at scale has the potential to deliver substantial economic benefits, and between ₹52,650 crore in India, depending on the pricing scenario. Additionally, this shift contributes to improved NUE and environmental sustainability through reduced GHG emissions.

Collectively, these findings establish that agronomic integration of nano-urea with conventional urea is a globally scalable strategy for curtailing nitrogen fertilizer doses while enhancing productivity, soil health, and environmental performance. Rather than replacing existing fertilizer systems, nano-fertilizers act as efficiency amplifiers, enabling sustainable intensification of agriculture. However, realizing their full potential requires extensive multi-location validation, refinement of crop- and region-specific application protocols, and deeper mechanistic understanding of plant-soil-microbe interactions. Strengthening this evidence base will be essential to mainstream nano-fertilizers as a cornerstone of climate-smart, energy-efficient, and economically resilient global agriculture.

Conservation Agriculture and Resource-Conserving Technologies

Impact of conservation agriculture in bridging yield gaps in Punjab and Haryana

Conservation Agriculture (CA) offers a scalable and cost-effective pathway to reduce technological yield gaps in rice–wheat systems of Punjab, Haryana, and Delhi. The table 3 and table 4 presents an estimate of the potential of CA in reducing technological yield gaps in rice and wheat across Punjab, Haryana, and Delhi. It assumes that CA can bridge about 5% of the existing yield gap, resulting in measurable gains in both productivity and farm income (Fig. 3). Under different adoption scenarios, the impacts become substantial. For rice, with a total area of 4.5 million ha, a 25% adoption of CA (1.125 million ha) would generate an additional 101,250 tonnes of rice, translating into an economic gain of 232.87 crore.

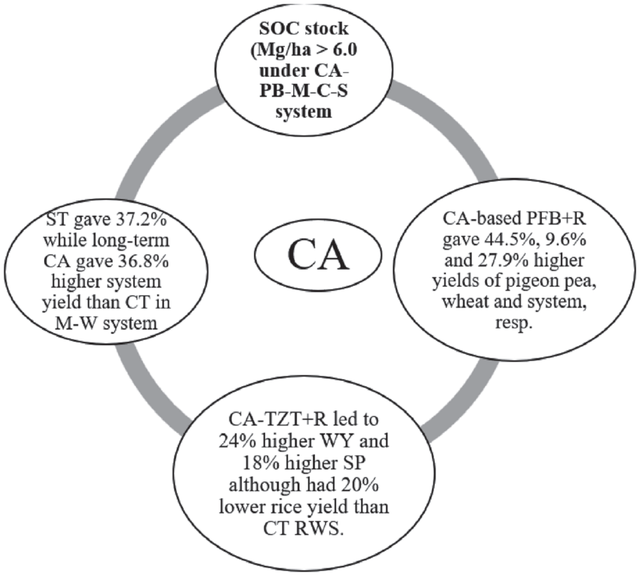

Fig. 3. Conservation agriculture-based systems in enhancing crop yield and economics

If CA adoption increases to 50% (2.25 million ha), the additional rice production would double to 202,500 tonnes, with an economic value of ₹465.75 crore. Similarly, for wheat, with a total area of 6.02 million ha and an assumed CA-induced yield increase of 0.075 t/ha (based on MSP 2024), a 25% adoption level (1.505 million ha) would result in an additional 112,875 tonnes of wheat, valued at

₹273.72 crore. At 50% adoption (3.01 million ha), the additional wheat production would rise to 225,750 tonnes, generating an economic benefit of ₹547.44 crore. These results highlight that even modest yield improvements—only 0.09 t/ha in rice and 0.075 t/ha in wheat—can lead to very large absolute gains in production due to the vast cultivated area in these states. The associated economic benefits are substantial, reaching up to ₹466 crore for rice and ₹547 crore for wheat. Importantly, CA is a scalable solution: as adoption increases from 25% to 50%, the gains nearly double. Therefore, promoting CA can significantly enhance food security, boost farmer incomes, and improve environmental sustainability, while effectively narrowing existing yield gaps. The linear scaling of benefits with adoption underscores CA's strong potential to enhance food security, improve farm incomes, and promote environmental sustainability while narrowing persistent yield gaps. Strategic policy support for CA dissemination can thus deliver high economic and ecological returns (Table 2 &3).

CA-based Integrated Crop Management (ICM)

The maize grain equivalents under CA-based ICMs (CA-based triple ZT maize and wheat with residues and green manures along with liquid biofertilizers / AMF) was 16.5–22.9% greater than that under the CT-based ICMs (Fig. 4). Also, these ICM practices gave 24.3–27.4% additional returns than the CT practices. However, in rice-wheat rotation, CA-based ICM modules had a positive impact on the system yields (10–14%) and farm economics (19–22%) than CT rice–wheat rotation. Synergistic effects of the ICM components reflected in complimenting the supply of nutrients besides conserving the soil fertility. If the findings are being eextrapolated benefits @25% adoption in northern India, there will be enormous impact of ICM modules in enhancing overall economic outcomes in cereal based system. If 25% of the maize-wheat rotation area in northern India adopts CA-based ICMs: The region would gain an additional 1.07–1.49 mt of maize grain equivalent annually. The net economic benefit would range between ₹1,458-1,644 crores each year. If 25% of the rice–wheat rotation area in northern India adopts CA-based ICMs: The system could produce an additional 1.5 to 2.1 mt of grains. The net economic benefit would range from ₹3,087–3,575 crores annually.

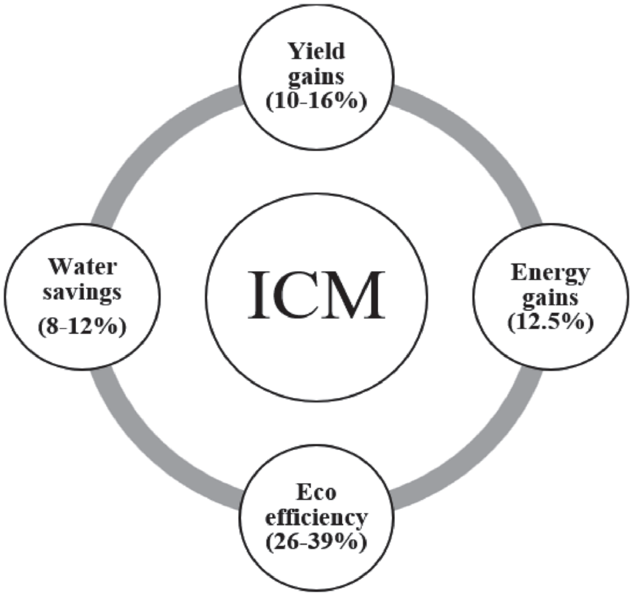

Fig. 4. Integrated crop management for enhancing crop yield, economics, water and energy use efficiency

Table 3. Potential of CA in reducing the technological yield gaps in rice

Rice area (mha) Punjab, Haryana, and Delhi (2024)	CA adoption %	CA potential to reduce the yield gap (~5% of gap)	Rice yield gain (t)	Value from rice (Crore INR) (Based on MSP-2024)
4.5	25% (1.125mha)	0.09 t/ha	101250	232.87
	50% (2.25mha)		202500	465.75

Table 4. Potential of CA in reducing the technological yield gaps in wheat

Area in wheat in (mha) Punjab, Haryana, and Delhi	CA adoption %	CA potential to reduce the yield gap (~5% of gap)	Wheat yield gain (t)	Value from rice (Crore INR) (Based on MSP-2024)
6.02	25% (1.505 mha)	0.075 t/ha	112,875	273.72
	50% (3.01 mha)		225,750	547.44

Cropping System Diversification and Integrated Farming Systems (IFS)

IFS models for Indo-Gangetic Plains

Diversification is one of the most effective agronomic strategies for enhancing farm productivity and improving resource use efficiency. The Division of Agronomy at ICAR-IARI has developed two Integrated Farming System (IFS) models, demonstrating that food production, expressed as rice equivalent yield (REY), can be substantially increased through the integration of crops with dairy, fishery, poultry, duckery, apiary, boundary plantations, biogas units, and vermicomposting (Figure and Table). The yield gains are remarkable: shifting from the traditional rice–wheat system (11.3 t/ha) to IFS can achieve 62.3 t/ha REY (Fig. 5 and 6), representing a 5–6× increase in productivity per hectare (Table 5). Even a modest 10% diversion of the total rice–wheat area (1.2 Mha) toward IFS can generate an additional 6.6 MT of food and ₹13,231 crore in economic benefits. Scaling up to 50% of the area could produce 33.1 MT of food, highlighting the immense potential of IFS for national food security and economic growth. The policy implication is clear: promoting climate-smart, resource-efficient, and integrated farming systems in key cereal-based regions can deliver significant agricultural, economic, and environmental benefits.

Table 5. Potential benefit of upscaling IFS in Indo Gangetic plain zones of India (Singh *et al.,* 2020, Shyam *et al.,* 2023)

S.No.	Particulars	values
1	Conventional rice –wheat yield	11.3 t/ha
2	Rice equivalent yield under IFS	62.3 t/ha
3	Rice-wheat area	12.0 Mha
4	Diversion of 10% of R-W area	1.2 Mha
5	Potential benefit food	6.6 MT
6	50% area diversification	33.1 MT
7	Economic benefit (10% area coverage basis)	13231.0 Crore INR

The eco-efficiency of IFS was estimated of Rs 43.9 as net return/profit per kg of CO_2 equivalent emission, while it was only Rs 13.2 under rice-wheat system (Fig. 5).

Weed Management Innovations

Managing Isoproturon resistance in Phalaris minor

Phalaris minor is an important and major weed of wheat causing huge losses in crop yield all across the wheat growing areas of 32 Mha in the country. Till now use of Isoproturin as post emergence herbicide is one of the most effective method control the weed but over the period because of continuous use of this herbicide, the weed Phalaris has developed the resistance and now the farmers are using increased doses and even than not able to control it. That's why this is causing huge negative impact on wheat yield. Further, Phalaris minor is a major weed in wheat, especially in the rice–wheat system of north-west India. Continuous use of isoproturon led to the evolution of herbicide-resistant biotypes. These resistant populations have now spread to over 1 million hectares, mainly in Punjab, Haryana, and western Uttar Pradesh. This resistance threatens wheat productivity, profitability, and sustainability.

The emergence and rapid spread of isoproturon-resistant Phalaris minor across more than 1 million hectares of

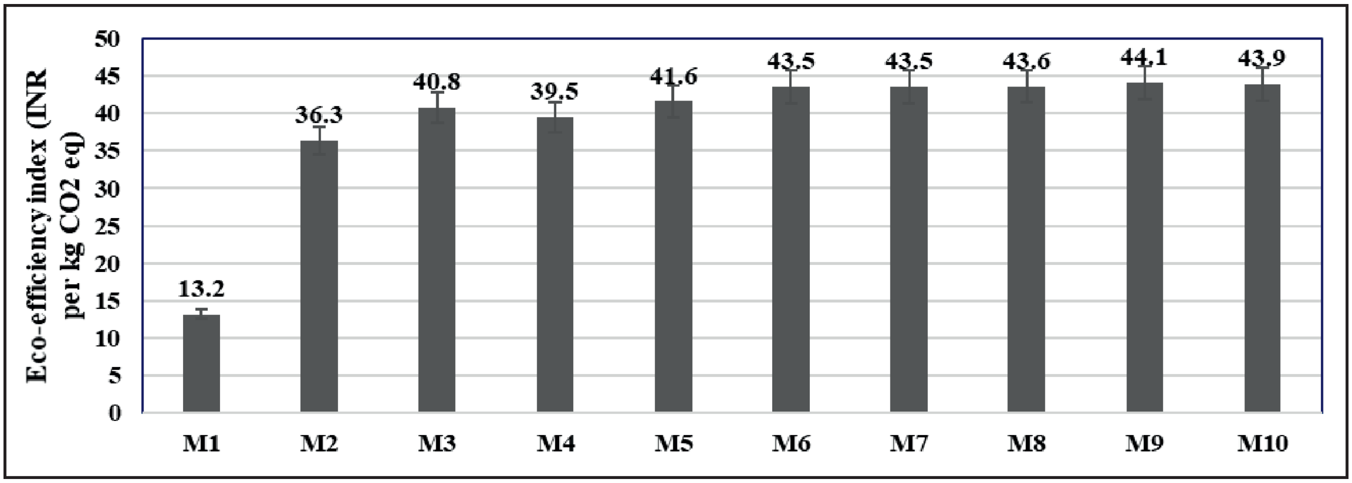

Fig. 5. Eco efficiency index (INR/kg of CO_2 eq emission under different IFS modules) [M_1, rice–wheat system, M_2, crop enterprise; M_3, Crop + Dairy; M4, crop + dairy + fishery; M_5, crop + dairy + fishery + poultry; M_6, crop + dairy + fishery + poultry + duckery; M_7, crop + dairy + fishery + poultry + duckery + apiary; M_8, crop + dairy + fishery + poultry + duckery + apiary + boundary plantation; M_9, crop + dairy + fishery + poultry + duckery + apiary + boundary plantation + biogas unit and M_{10}, crop + dairy + fishery + poultry + duckery + apiary + boundary plantation + biogas unit + vermi-compost]

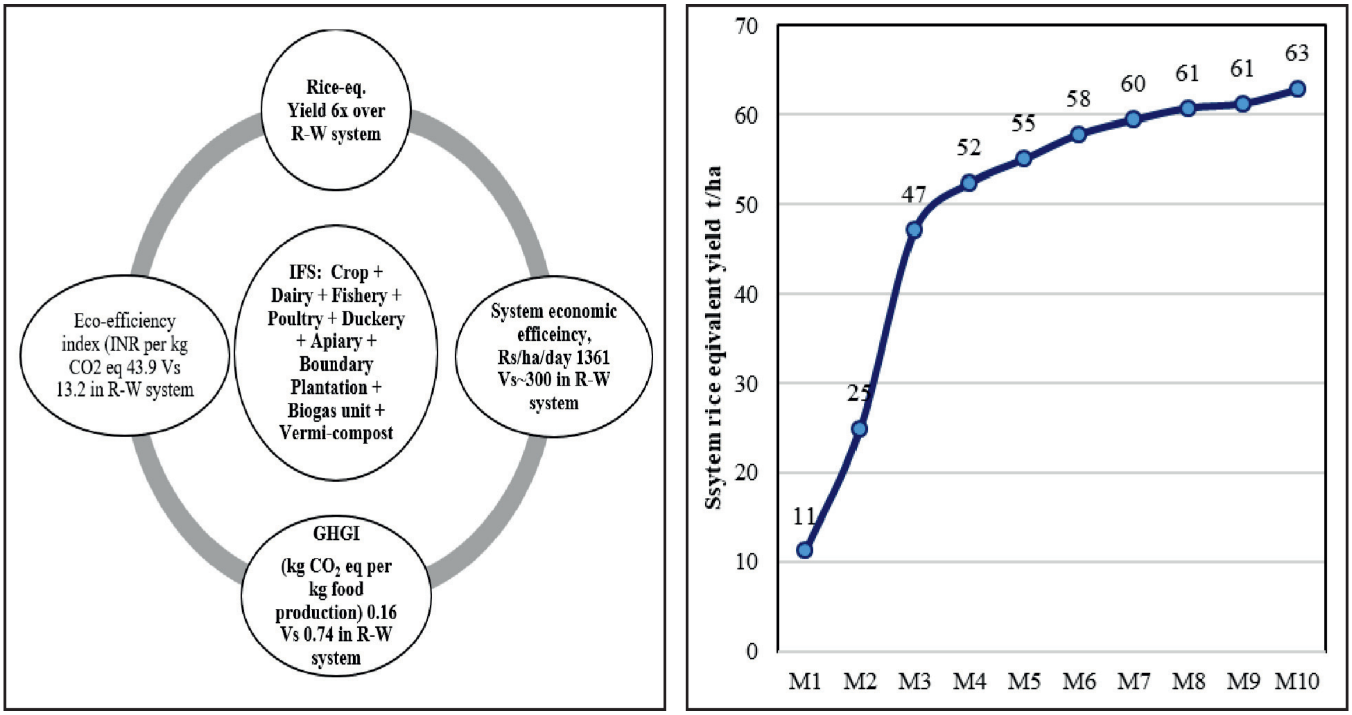

Fig. 6. Effect of IFS in enhancing the productivity and income on per ha basis

India's rice–wheat system, particularly in Punjab, Haryana, and western Uttar Pradesh, posed a serious threat to wheat productivity and farm incomes. Timely research-led identification and registration of alternative herbicides e.g. clodinafop-propargyl, sulfosulfuron, and fenoxaprop-p-ethyl enabled effective control of this resistant weed, preventing large-scale yield losses. The widespread adoption of these technologies by nearly all wheat growers in the north-western plains has resulted in estimated annual economic savings of ₹1,127 crore, highlighting the critical role of responsive agronomic innovations in safeguarding national food security. This case underscores the importance of proactive resistance management, diversified herbicide use, and continuous investment in adaptive research and extension systems to enhance the resilience and sustainability of India's cereal production systems.

Herbicide + dormancy-breaker technology

A novel herbicide plus dormancy-breaker technology, reported for the first time globally, offers a transformative solution for weed management in soybean and wheat systems. By integrating potassium nitrate (KNO, 6%) as a dormancy-breaking agent with reduced-dose herbicide tank mixes, this approach enhances weed seed germination synchrony and improves subsequent control efficiency. Field results show exceptional performance, achieving up to 99% reduction in annual weeds and 83% in perennial weeds, while lowering herbicide use by 25% and overall weed management costs by 50%. The technology also contributes to nutrient-use efficiency, reducing potassium and nitrogen inputs by 8.76 kg and 3.12 kg per hectare, respectively. In soybean, it increases net returns by ₹10,407 per hectare, with a potential national income gain of ₹14,050 crore annually upon large-scale adoption. With demonstrated applicability across central and northern soybean belts and all major wheat-growing states, this innovation aligns strongly with India's goals of sustainable intensification, input-use efficiency, and climate-resilient agriculture under the vision of Viksit Bharat @2047.

Weed management option in zero-till DSR systems

Efficient weed management is a critical enabler for the successful scaling of zero-till direct-seeded rice (DSR), a key water- and labour-saving technology for the Indo-Gangetic Plains. The sequential application of pyrazosulfuron (PE) followed by cyhalofop-butyl and bispyribac-Na has demonstrated robust, season-long weed control under zero-till DSR, significantly reducing labour requirements by 40–45% and weeding costs by 80–85%. Beyond weed suppression, this approach also provides ancillary benefits such as control of plant-parasitic nematodes and enhanced water and nutrient use efficiencies, strengthening overall system resilience. Economic analysis shows an increase in net returns of ₹10,320/ha, with a potential additional gain of ₹1,032 crore if adopted across 1 million hectares of the rice–wheat system. With high relevance for Punjab, Haryana, and western Uttar Pradesh, this technology aligns strongly with national priorities on resource conservation, climate-smart agriculture, and sustainable intensification.

Quantified Impacts and Implications of Agronomic Innovations

The integrated assessment of agronomic technologies clearly demonstrates that science-based management interventions have delivered transformative and quantifiable impacts on Indian agriculture at both farm and national scales (Table 6). Across diverse cropping systems, these innovations have consistently enhanced productivity while simultaneously improving profitability, resource-use efficiency, and environmental performance. Technologies such as critical-stage irrigation scheduling, conservation agriculture, integrated farming systems, precision nutrient management, and sub-surface drip fertigation illustrate that even modest per-hectare gains, when scaled over large cultivated areas, translate into substantial national-level benefits in terms of food production, economic returns, and fiscal savings. Importantly, the cumulative evidence underscores that many of the persistent challenges facing Indian agriculture; yield plateaus, low nitrogen and water use efficiencies, rising production costs, herbicide resistance, and increasing greenhouse gas emissions are predominantly agronomic in nature and can be effectively addressed through improved management rather than increased input intensity. By enhancing input-use efficiency, reducing environmental externalities, and strengthening climate resilience, these agronomic innovations directly respond to second-generation Green Revolution challenges and reposition agronomy as a strategic driver of sustainable intensification. The synthesis further highlights the need for systematic documentation, impact quantification, and policy-aligned scaling of proven agronomic technologies to fully harness their potential in advancing national food security, farmer livelihoods, and long-term environmental sustainability.

Prospects and Policy-Relevant Pathways for Scaling Agronomic Innovations

The present synthesis highlights a coherent and reinforcing pathway through which agronomic innovations can drive large-scale agricultural transformation when effectively translated, adopted, and supported by enabling policies (Fig 7). Scientific advances generated through agronomic research attain their full value only when translated into field-ready management practices that are technically sound, economically viable, and adaptable to diverse agro-ecological conditions. Successful adoption and implementation of such practices by farmers lead to demonstrable improvements in crop productivity, farm profitability, resource-use efficiency, and environmental sustainability. When these benefits are realized across substantial areas, they scale into significant national-level outcomes, including enhanced food security, reduced fertilizer and water dependency, improved economic efficiency of agricultural systems, and greater resilience to climatic variability.

Crucially, the prospects of agronomic innovation extend beyond immediate productivity gains to the establishment of a dynamic feedback loop between field-level outcomes and policy frameworks. Evidence generated from large-scale adoption provides a robust basis for policy feedback, guiding targeted investments, refinement of national missions, and prioritization of future research and extension efforts. Such policy-informed reinforcement strengthens institutional support for agronomic technologies, accelerates their dissemination, and fosters continuous innovation. Harnessing this translation–adoption–scaling–policy feedback continuum will be central to realizing the full potential of agronomic innovations and advancing resilient, resource-efficient agricultural systems aligned with India’s vision for sustainable growth.

The agronomic technologies are strongly aligned with India’s major national missions aimed at enhancing productivity, resource-use efficiency, and climate resilience Innovations in precision irrigation, sub-surface drip fertigation, and deficit water management directly support the objectives of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) by advancing the principle of “Per Drop More Crop” through substantial improvements in water productivity and irrigation efficiency. Nutrient management interventions such as neem-coated urea, precision nitrogen scheduling, and the integrated use of nano-fertilizers are closely aligned with the PM-PRANAM initiative, as they reduce chemical fertilizer consumption, enhance nitrogen-use efficiency, and contribute to rationalization of fertilizer subsidies while lowering environmental externalities. Conservation agriculture, integrated crop management, and diversified farming systems strengthen climate-smart agriculture pathways by improving soil health, reducing greenhouse gas emissions, and enhancing resilience to climatic variability. Collectively, the demonstrated impacts of these technologies position agronomic innovation as a critical enabler of India’s long-term development agenda and directly contribute to the realization of Viksit Bharat @2047 by fostering sustainable intensification, economic efficiency, and climate-resilient agricultural growth.

Agronomic Technologies Beyond Yield

Evidence synthesized demonstrates that agronomic technologies have impacts far exceeding incremental yield enhancement, warranting a repositioning of agronomy as a strategic discipline central to national food-system transformation rather than a supporting component of crop im-

Table 6. Quantified impacts and national-scale contributions of major agronomic technologies

Technology/ innovation	Cropping system/scale	Productivity enhancement	Expected potential economic returns	Resource-use efficiency gains	Environmental and climate benefits	Contribution to addressing second-generation green revolution challenges
CRI-stage irrigation in wheat	Wheat (~32 Mha)	20–30% yield contribution; + 22–34 Mt wheat annually	₹54,000–81,000 crore/yr	Higher water productivity through precise timing	Reduced over-irrigation losses; lower energy	Converts input timing into yield use gain; stabilizes productivity under water stress
Integrated Farming Systems (IFS)	Rice–wheat diversification (IGP)	REY: 11.3 → 62.3 t/ha (5–6 × increase)	₹13,231 crore (10% area); ₹66,000+ crore potential at 50% area	Recycling of nutrients, water & biomass	Eco-efficiency ↑ (₹43.9 vs ₹13.2/kg CO_2-eq)	Tackles income stagnation, risk, employment & system vulnerability
Conservation agriculture (CA)	Rice–wheat (Punjab, Haryana, Delhi)	Yield gap reduction ~5%; +0.09 t/ha rice, +0.075 t/ha wheat	₹233–466 crore (rice); ₹274–547 crore (wheat)	Improved WUE, NUE, energy savings	Lower GHG emissions; soil carbon retention	Addresses yield plateaus, residue burning, soil degradation
CA-based Integrated Crop Management (ICM)	Maize–wheat; rice–wheat	+10–23% system yield	₹1,458–1,644 crore (maize–wheat @ 25% adoption); ₹3,087–3,575 crore (rice–wheat)	NUE & soil fertility enhancement	Reduced nutrient losses	Corrects inefficiencies of blanket input use
Sub-surface drip fertigation (SSDF)	Maize–wheat (~42.7 Mha)	+10–18% yield; + 16–25 Mt grain	₹39,015–58,274 crore/yr	25% nutrient saving; major WUE gains	Reduced leaching, N_2O emissions	Integrates water–nutrient precision; climate-smart intensification
Neem-coated urea	All N-fertilized crops	Yield maintained with lower N	₹6,000–7,000 crore subsidy ssaving/yr	NUE ↑ 10–15%; ~7 kg N/ha saved	Lower volatilization & leaching	Reduces fertilizer misuse & import dependence
Nano-urea + conventional urea	Cereals & oilseeds	Yield sustained at 25% N reduction	₹52,650 crore subsidy saving (India)	25% N saving; higher NUE	~236 Mt CO_2-eq mitigation (global potential)	Addresses energy, climate & efficiency concerns
Herbicide resistance management (Phalaris minor)	Wheat (~1 Mha affected)	Prevented major yield losses	₹1,127 crore/yr savings	Optimized herbicide use	Reduced chemical load	Tackles resistance & sustainability risks
Herbicide + dormancy-breaker technology	Soybean & wheat	Weed control: 83–99%	₹14,050 crore national gain (soybean)	25% herbicide saving	Lower chemical footprint	Innovation against escalating weed resistance
Weed management in zero-till DSR	Rice–wheat (~1 Mha)	Yield stability under DSR	₹1,032 crore additional returns	Water & labour savings	Reduced CH_4 emissions	Enables scaling of water-saving DSR

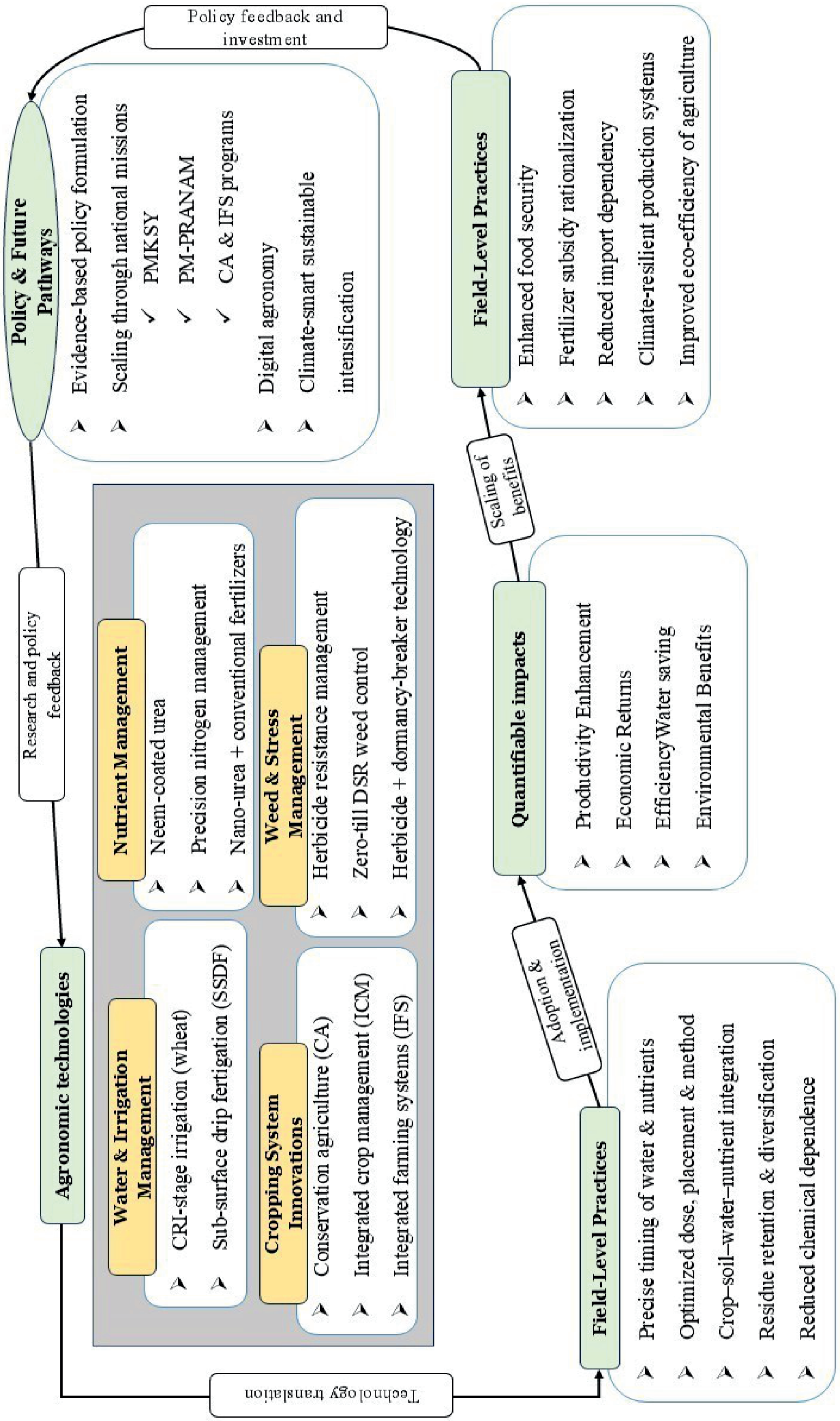

Fig. 7. Framework for scalable agronomic technologies to field-level practices, quantified impacts, and national policy outcomes

provement. Data from large-scale adoption of agronomic interventions show that modest plot-level gains often in the range of 5–30% improvements in yield, water productivity, or nutrient-use efficiency; translate into disproportionately large national outcomes when applied across millions of hectares, generating annual economic benefits ranging from several hundred crores to over ₹80,000 crore. Beyond productivity, agronomic innovations such as precision irrigation, CA, IFS, and advanced nutrient management have demonstrably reduced fertilizer and water consumption by 25–60%, mitigated GHGs emissions, enhanced soil carbon stocks, and improved system resilience to climatic variability. These outcomes directly address second-generation green revolution challenges, including resource depletion, environmental degradation, and income instability, which cannot be resolved through genetic gains alone. The cumulative evidence underscores that agronomy governs the efficiency, sustainability, and resilience of food production systems at scale, enabling the transition from plot-scale optimization to integrated, national-level food-system transformation. Recognizing and investing in agronomy as a strategic science is therefore essential for achieving sustainable intensification, fiscal efficiency, and long-term food and environmental security.

The present synthesis demonstrates that agronomic innovations constitute a powerful and scalable pathway for enhancing productivity, profitability, and environmental sustainability in Indian agriculture. Therefore, it can be concluded that many of the agronomic technologies impacted hugely in enhancing farm productivity, income and also reducing the environmental footprints. The revenue generation because of wider adoption these agronomic technologies ranged from ₹450 crore in minimizing yield gaps in Punjab and Haryana and upto ₹80 thousand crore from adoption of irrigation scheduling at CRI stage of wheat. Technologies such as precision irrigation scheduling, integrated farming systems, conservation agriculture, subsurface drip fertigation, improved nitrogen-use strategies, and resistance-aware weed management have shown substantial potential to bridge yield gaps, improve resource-use efficiency, and reduce ecological footprints. Further, agronomy is no longer a supporting discipline; it is a central pillar of India's sustainable food systems transformation. Harnessing its full potential through science-backed scaling, digital decision tools, and supportive policies can significantly enhance food security, farmer incomes, and ecological resilience—making agronomic innovation a cornerstone of India's pathway to a climate-smart, resource-efficient, and prosperous agricultural future. The findings underscore that many of India's contemporary agricultural challenges are primarily agronomic rather than genetic in nature, and can be effectively addressed through science-based management. Strategic scaling of these proven practices, supported by policy alignment, institutional backing, and robust extension systems, can play a pivotal role in achieving sustainable intensification and advancing the vision of Viksit Bharat @2047.

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