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Redesigning rice-wheat systems of the northwest indo-gangetic plains through laser land leveling, crop diversification and artificial intelligence: A critical review

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Abstract
The rice-wheat production system of the North-Western Indo-Gangetic Plains (NWIGP) has played a critical role in ensuring national food security; however, prolonged mono-cropping, excessive groundwater extraction, and inefficient resource use have led to declining system productivity and environmental stress. Redesigning this system through the integration of laser land leveling (LLL), crop diversification, and artificial intelligence (AI) offers a promising pathway toward sustainable intensification. Empirical studies from the NWIGP indicate that laser land leveling improves field uniformity and reduces irrigation water use by 20-30%, while enhancing water productivity by 15-25% and increasing rice and wheat yields by 5-10% compared to conventionally leveled fields. Additionally, LLL has been shown to lower energy consumption for irrigation by 15-20% and reduce nitrogen losses due to improved moisture distribution. Crop diversification, particularly the substitution of rice with maize, pulses, or oilseeds, has demonstrated groundwater savings of 30-50% and net income gains ranging from 20-40%, along with measurable improvements in soil organic carbon and nutrient-use efficiency. The incorporation of artificial intelligence further strengthens system performance by enabling real-time, site-specific decision-making. AI-driven models for irrigation scheduling and nutrient management have been reported to reduce fertilizer use by 10-20% and irrigation events by 15-25% without yield penalties, while improving input-use efficiency and reducing greenhouse gas emissions. The synergistic integration of LLL, diversified cropping systems, and AI-based decision support tools facilitates a transition from resource-intensive to precision- and knowledge-driven agriculture. This redesigned rice-wheat system enhances resilience to climate variability, restores resource-use efficiency, and supports long-term sustainability and profitability in the NWIGP under increasing biophysical and socio-economic constraints.

Keywords: Rice-wheat system, laser land leveling, crop diversification, artificial intelligence, resource-use efficiency, indo-gangetic plains

Introduction

The Indo-Gangetic Plains represent one of the most agriculturally productive landscapes in the world, with the north-western Indo-Gangetic Plains (NW-IGP) serving as the epicenter of cereal production in South Asia. Since the Green Revolution of the late 1960s, the rice-wheat cropping system has dominated this region and has been instrumental in ensuring national food self-sufficiency (Ladha *et al.*, 2003). Supported by assured irrigation, mechanization, improved cultivars, and price incentives, the system delivered high and stable yields for several decades.

Over time, however, the intensive and largely unidimensional nature of the rice-wheat system has generated multiple sustainability challenges. Declining groundwater tables, deterioration of soil physical and biological properties, plateauing yields, increasing energy demand, and rising environmental externalities have become widespread across Punjab, Haryana, and western Uttar Pradesh (Bouman *et al.*, 2007; Jat *et al.*, 2016; Ladha *et al.*, 2014) [5, 21, 30]. These constraints are interlinked and reinforce one another, making conventional input-intensive strategies increasingly ineffective. Moreover, research emphasizes that the future of cereal production in the NW-IGP depends on system redesign rather than piecemeal interventions (Gathala *et al.*, 2011; Naresh *et al.*, 2020) [11, 37]. System redesign requires rethinking how land, water, crops, and information are managed. In this context, laser land leveling, crop diversification, and artificial intelligence

(AI)-enabled precision agriculture have emerged as complementary innovations capable of transforming rice-wheat systems into more resilient, efficient, and climate-adaptive production systems.

1. Rice-Wheat Systems of the NW-IGP: Productivity Gains and Emerging Limits

Structural Intensification and Resource Dependence

Laser land leveling LLL reduced irrigation water use by 20-27% in rice and 12-16% in wheat through improved uniformity of water advance and reduced over-irrigation (Gathala *et al.*, 2023; Kumar *et al.*, 2023) [14, 29]. Grain yields increased by 6-9% across seasons, while electricity consumption for groundwater pumping declined by 18-24%, resulting in higher energy productivity and reduced variable costs (Jat *et al.*, 2021) [23]. Similar trends were reported under farmers' fields in western Uttar Pradesh, where LLL improved irrigation efficiency and operational timeliness under conservation-oriented management (Naresh *et al.*, 2022) [39, 43].

Crop diversification markedly reduced system-level resource dependence. Substitution of rice with maize or inclusion of short-duration legumes such as mung-bean lowered irrigation demand by 35-50% and increased net returns by 22-34% compared with continuous rice-wheat systems (Khanal *et al.*, 2021) [28]. Improvements in soil quality were evident, with soil organic carbon increasing by 0.25-0.40 Mg ha^{-1} over four crop cycles due to reduced puddling intensity and enhanced residue inputs (Gathala *et al.*, 2023; Naresh *et al.*, 2023) [14, 40, 41]. Nitrogen-use efficiency improved by 18-25%, reflecting contributions from biological nitrogen fixation and improved nutrient synchrony. Moreover, artificial intelligence (AI) further enhanced resource-use efficiency. Machine-learning-based advisory systems integrating satellite vegetation indices, soil moisture sensors, and weather data reduced irrigation and fertilizer inputs by 15-22% without yield penalties (Gangwani, 2024) [10]. These tools improved temporal precision of management decisions, particularly under increasing climatic variability.

Table 1: Effects of laser land leveling (LLL) on water use, energy consumption, and yield in rice-wheat systems of the NW IGP

Intervention	Crop	Water saving (%)	Energy saving (%)	Yield change (%)	Scientist & year
Laser land leveling	Rice	20-27	18-24	+6 to +9	Jat *et al.* (2021)
Laser land leveling	Wheat	12-16	15-22	+5 to +8	Kumar *et al.* (2023)
LLL + conservation practices	Rice-Wheat	22-30	20-25	+7 to +10	Naresh *et al.* (2022)
Farmer-managed LLL fields	Rice-Wheat	18-25	15-21	+6 to +8	Gathala *et al.* (2023)

Table 2: Impacts of crop diversification and AI-based precision management on resource-use efficiency and system performance

System/Technology	Water reduction (%)	Net return increase (%)	Soil organic carbon change	Input Reduction (%)	Scientist & year
Rice-wheat-mungbean	35-45	25-34	+0.25-0.35 Mg ha^{-1}	N fertilizer -18-22%	Khanal *et al.* (2021)
Maize-wheat rotation	40-50	22-30	+0.30-0.40 Mg ha^{-1}	Irrigation -35-45%	Gathala *et al.* (2023)
Diversified systems with LLL	30-45	20-32	+0.28-0.38 Mg ha^{-1}	Energy -20-25%	Naresh *et al.* (2023)
AI-based irrigation & nutrient advisory	15-22	10-18	Maintained	Water & fertilizer -15-22%	Gangwani (2024)

Groundwater Depletion and Energy Intensification

Northwestern Indo-Gangetic Plains (NW IGP) clearly demonstrates that the rice-wheat (RW) system is a major driver of groundwater depletion and energy intensification (Table 3). Rice-based rotations required substantially higher irrigation inputs (≈1200-1300 mm ha^{-1}) and more irrigation events [14-15] compared with maize-based alternatives. Consequently, total energy consumption in conventional RW systems ranged from 18,000 to 19,000 MJ ha^{-1}, largely attributed to groundwater pumping and intensive tillage operations (Jat *et al.*, 2019; Ladha *et al.*, 2020) [22, 31]. Irrigation alone accounted for nearly 45-50% of total energy use, reinforcing the close coupling between groundwater exploitation and rising energy demand.

In contrast, diversification of RW systems markedly reduced both water and energy use. Substitution of rice with maize lowered irrigation demand by nearly 40% and reduced energy inputs by approximately 41%, while improving subsequent wheat yields (Table 3). These results confirm that crop diversification offers a strong pathway to reduce groundwater abstraction without compromising system productivity (Jat *et al.*, 2019) [22].

Conservation agriculture (CA)-based interventions further moderated groundwater and energy pressures (Table 4). However, zero or reduced tillage combined with residue retention decreased irrigation water use by 15-20% and energy consumption by 12-18%, while maintaining crop yields (Gathala *et al.*, 2015) [12]. Precision irrigation and mechanization improved energy efficiency by up to 21%, indicating the importance of technological optimization (Bowman *et al.*, 2018) [6]. Moreover, Naresh *et al.* (2018, 2020) demonstrated that laser land leveling, zero-till wheat, and residue retention reduced groundwater withdrawal by 20-25% and diesel energy use by 25-30%, while enhancing wheat yields by 5-8% (Table 4). These findings highlight the practical relevance of CA technologies under farmers' field conditions in the NWIGP. The integrated evidence from Tables and indicates that continued reliance on conventional puddled transplanted rice will accelerate groundwater depletion and energy intensification. In contrast, diversification, conservation agriculture, and precision water management significantly improve water- and energy-use efficiency, offering a robust pathway for sustainable intensification of RW systems in the NW IGP.

Table 3: Groundwater use, irrigation intensity and energy consumption in rice-wheat and alternative systems of NW Indo-Gangetic Plains

Scientist &Year	Cropping System	Irrigation Water Use (mm ha-1)	Irrigation Events (no.)	Energy Use (MJ ha-1)	Grain Yield (t ha-1)	Key Results
Jat *et al.* (2019)	Rice-Wheat	~1200	14	~18,500	Rice 6.2; Wheat 4.5	High groundwater withdrawal and pumping energy
Jat *et al.* (2019)	Maize-Wheat	~700	5	~11,000	Maize 7.1; Wheat 5.2	~40% less water use and ~41% lower energy input
Ladha *et al.* (2020)	Rice-Wheat (PTR)	1200-1300	14-15	18,000-19,000	Rice ~6.0; Wheat ~4.3	Irrigation contributes 45-50% of total energy use
Gathala *et al.* (2015)	CA-based Rice-Wheat	1000-1050	11-12	15,000-16,000	Rice 6.1; Wheat 4.6	15-20% water saving with similar yields
Bowman *et al.* (2018)	Rice-Wheat + Precision Irrigation	~1050	~12	~14,500	Rice 6.2; Wheat 4.7	Energy use reduced by up to 21%

Table 4: Impact of conservation and management interventions on groundwater depletion and energy intensification in NW IGP rice-wheat systems

Scientist & Year	Intervention / Practice	Change in Groundwater Use	Change in Energy Use	Yield Effect	Major Outcome
Naresh *et al.* (2018)	Laser land leveling + improved irrigation	↓ water use by 20-25%	↓ pumping energy by 18-22%	Maintained yields	Improved irrigation efficiency and aquifer sustainability
Naresh *et al.* (2020)	Zero-till wheat + residue retention	↓ groundwater extraction	↓ diesel energy by 25-30%	↑ Wheat yield (5-8%)	Enhanced energy productivity under CA
Gathala *et al.* (2015)	Zero/reduced tillage + residue retention	↓ irrigation by 15-20%	↓ energy use by 12-18%	Stable/ slightly ↑	Strong water-energy nexus improvement
Jat *et al.* (2019)	Rice replacement with maize	Large reduction in pumping	↓ total energy by ~41%	↑ system productivity	Most effective diversification option
Ladha *et al.* (2020)	CA + AWD at system scale	Slower water-table decline	↓ irrigation energy	No yield penalty	Reduced pressure on deep aquifers
Bowman *et al.* (2018)	Precision irrigation & mechanization	Optimized abstraction	↓ energy use up to 21%	Maintained yields	Higher energy efficiency
Ladha *et al.* (2020)	Conventional PTR continuation	Water table decline ~0.2 m yr-1	High diesel/electricity use	Yield stagnation	Environmentally unsustainable

Soil Degradation and Yield Stagnation

Rice and wheat yields increased rapidly during the early Green Revolution phase but have shown clear stagnation in recent decades, despite continued intensification of fertilizer and irrigation inputs (Dawe *et al.*, 2000; Ladha *et al.*, 2020) [8, 31]. However, substantial decline in soil organic carbon, accompanied by increasing bulk density, reflecting structural degradation associated with repeated puddling for rice and intensive tillage for wheat (Singh *et al.*, 2018; Jat *et al.*, 2021) [54, 23]. Available potassium levels have declined markedly over time, while the proportion of fields deficient in zinc has increased, highlighting progressive nutrient mining and emerging micronutrient constraints (Singh *et al.*, 2018)[54]. The sharp increase in groundwater depth underscores the growing water scarcity in the region and its role as a major limiting factor for sustaining rice-wheat productivity (Jat *et al.*, 2023) [17]. Moreover, effects of conservation agriculture and precision nutrient management practices on crop yield, soil organic carbon, and water productivity in rice-wheat systems. Zero-tillage wheat consistently outperformed conventional tillage, with yield gains of 5-10% attributed to improved soil structure, better root growth, and enhanced nitrogen use efficiency (Jat *et al.*, 2021; Gathala *et al.*, 2022) [23, 13]. Residue retention further increased soil organic carbon and water productivity, while combined application of zero tillage, residue retention, and site-specific nutrient management resulted in the highest improvements in yield stability and soil health indicators (Naresh *et al.*, 2021, 2023) [38]. However, the reduced yield benefits under conditions of severe groundwater depletion emphasize that conservation practices alone cannot fully offset regional water stress (Ladha *et al.*, 2020; Jat *et al.*, 2023)[31, 17].These patterns indicate that the conventional rice-wheat system has reached its biophysical ceiling.

2. Laser Land Leveling: Enhancing Physical Resource Efficiency

Water Use and Irrigation Productivity

Northwest Indo-Gangetic Plains (NW IGP) confirm that laser land leveling (LLL) substantially improves irrigation performance and water productivity in rice-wheat systems. Empirical data indicate that LLL reduces the volume and duration of irrigation applied compared to traditional leveling, primarily by enhancing field surface uniformity and reducing ponding and tail-end losses (Jat *et al.* 2011; Aryal *et al.* 2015) [19, 1]. Quantitative assessments report water savings of about 15-30% with laser land leveling across RW systems, leading to greater water use efficiency without compromising grain yields (Bera *et al.* 2024)[60]. Yield responses to LLL indicate moderate but consistent improvements in both rice and wheat. Uniform moisture distribution under LLL improves crop establishment and reduces abiotic stress, contributing to yield gains of \~5-10% in comparative trials (Aryal *et al.* 2015; Bera *et al.* 2024)[1]. Land leveling also supports water productivity gains: average WPi values reached \~0.52 kg m^{-3} in Punjab LLL fields *versus* \~0.33 kg m^{-3} under uneven conditions, and up to 0.91 kg m^{-3} in Modipuram, demonstrating 2-fold improvements over traditional practices (Bera *et al.* 2024)[60].

Kumar *et al.* (2025)[61] showed that LLL enhanced irrigation efficiency enough to raise pre-monsoon groundwater levels by \~7.8 m compared to baseline scenarios, highlighting its potential for groundwater sustainability. Combined with conservation agriculture practices (*e.g.*, zero tillage and residue retention), LLL can synergistically increase water productivity and yield stability in RWCS (Naresh *et al.* 2021) [38]. Moreover, systematic reviews indicate that transitioning from flood irrigation and farmer leveling to LLL and other precision techniques could save 20-60% of irrigation water across the NW IGP. Despite these gains, adoption constraints such as high machinery costs and access to service providers persist. Institutional support and private sector service provision have been identified as critical enablers for widespread LLL uptake, particularly among smallholders in NW IGP landscapes.

Table 5: Effect of laser land leveling on irrigation water use and productivity in rice-wheat systems of NW IGP

Crop	Leveling method	Irrigation water applied (mm)	Water saving (%)	Irrigation time reduction (h ha-1season-1)	Irrigation water productivity (kg m-3)	Scientist & Year
Rice	Farmer leveling	1400-1600	-	-	0.30-0.35	Jat *et al.* (2011)
Rice	Laser leveling	1050-1200	20-30	45-70	0.45-0.55	Aryal *et al.* (2015);

Table 6: Yield response, economic gains, and recent system-level impacts of laser land leveling in NW IGP

						Bera *et al.* (2024)
Wheat	Farmer leveling	450-500	-	-	0.90-1.00	Humphreys *et al.* (2016)
Wheat	Laser leveling	350-400	15-25	8-12	1.20-1.40	Jat *et al.* (2020); Bera *et al.* (2024)

Parameter	Farmer leveling	Laser land leveling	Improvement (%)	Key observations	Scientist & Year
Rice yield (t ha-1)	5.0-5.4	5.5-6.0	5-10	Uniform crop stand, reduced water stress	Aryal *et al.* (2015); Bera *et al.* (2024)
Wheat yield (t ha-1)	4.3-4.7	4.8-5.2	6-9	Improved soil moisture uniformity	Jat *et al.* (2020)
Energy use (kWh ha-1)	950-1100	700-800	20-30	Reduced pumping duration	Naresh *et al.* (2021)
Net returns (₹ ha-1)	75,000-82,000	88,000-95,000	10-15	Lower irrigation cost, stable yields	Bera *et al.* (2024)
Groundwater impact	Declining	Stabilizing	-	Pre-monsoon water table rise (~7-8 m)	Kumar *et al.* (2025)

Yield Stability and Economic Performance

Laser land leveling contributes to yield stability by ensuring uniform crop establishment and synchronized crop growth in the north-western Indo-Gangetic Plains demonstrate that laser land leveling (LLL) significantly improves yield stability and economic performance in rice-wheat systems. Laser leveling reduced micro-topographic variability, leading to more uniform ponded water depth in rice and improved soil moisture distribution in wheat and rice grain yield increased consistently by 6-10% and wheat by 5-8% over conventional leveling, with lower inter-seasonal variability under both normal and deficit irrigation conditions (Jat *et al.*, 2021; Singh *et al.*, 2022; Kumar *et al.*, 2023) [23, 51, 29].

Singh *et al.* (2024) [53] showed that the coefficient of variation in grain yield declined by 20-35% in laserleveled fields, indicating reduced production risk and greater resilience to climatic variability. Improved crop stand uniformity and synchronized maturity contributed to better harvest indices in both crops. Water savings of 15-30% in rice and 10-20% in wheat were recorded, leading to substantial reductions in pumping duration and energy use (Naresh *et al.*, 2022; Aryal *et al.*, 2023) [39, 43, 2].

Economic performance improved markedly due to combined yield gains and lower irrigation and labor costs. Kaur *et al.* (2023) [26] reported reductions in cost of cultivation by 3,500-6,000 ha ₹ $^{-1}$ per season, while net returns increased by 12-20% compared to traditional leveling. Benefit-cost ratios ranged from 1.35 to 1.60 under LLL, reflecting improved profitability even under rising energy prices. When the initial cost of leveling was amortized over 3-seasons, cumulative additional profits of 25,000-40,000 ha ₹ $^{-1}$ were realized in rice-wheat rotations (Naresh *et al.*, 2023) [40, 41]. These results confirm that laser land leveling enhances both yield stability and economic sustainability of intensive rice-wheat systems.

3. Crop Diversification: Rebuilding Ecological Resilience

Need for Diversification in Rice-Wheat Landscapes

Diversification of rice-wheat landscapes is essential to reverse yield stagnation, declining resource-use efficiency, and soil degradation under intensive monoculture and in the Eastern and Western Indo-Gangetic Plains show that diversified rice-based systems integrating maize, legumes, vegetables, or oilseeds significantly enhanced system productivity and farm profitability compared with continuous rice- wheat rotations. Upadhaya *et al.* (2022)[62] reported substantial gains in rice-equivalent yield and benefit- cost ratio in diversified systems, accompanied by marked improvements in soil biological activity, indicating more efficient nutrient cycling and improved soil functional health.

Jat *et al.* (2022)[63] found that diversified systems such as maize-wheat-mungbean increased system productivity, net economic returns, and protein yield, while reducing irrigation water use relative to puddled rice-wheat systems. The inclusion of legumes significantly improved nitrogen availability and nutrient-use efficiency, highlighting the role of biological processes in sustaining productivity under reduced input conditions. Naresh *et al.* (2023) [41] further confirmed that diversification combined with conservation agriculture practices improved soil organic carbon, aggregation, and water productivity in rice-wheat landscapes. These results showed that replacing rice with less water-intensive crops and incorporating legumes reduced pressure on water resources while enhancing soil resilience and crop yield stability. Moreover, these findings indicate that the conventional rice-wheat monoculture intensifies ecological stress and economic vulnerability, whereas diversified systems enhance productivity, profitability, and resilience to climate variability. The growing body of evidence confirms that diversification is a scientifically validated necessity for sustainable intensification in rice-wheat dominated agroecosystems.

Table 7: System productivity and profitability of crop diversification for rebuilding ecological resilience

Diversification system	Cropping sequence / components	System productivity (t ha-1yr-1, REY*)	B:C ratio	Water productivity (kg m-3)	Nutrient use efficiency (kg grain kg-1nutrient)	Soil organic carbon change (% yr-1)	GHG emission intensity (kg CO2e t-1)	Ecological resilience contribution	Scientist(s) & year
Rice-Wheat (baseline)	Rice → Wheat	9.0	1.57	0.65	45	+0.05	420	High input use, low resilience	Ladha *et al.*, 2003; Pathak *et al.*, 2011; Naresh *et al.*, 2018
Rice-Wheat-Mungbean	Rice → Wheat → Mungbean	10.8	1.83	0.78	58	+0.12	360	Improved N cycling and pest break	Yadav *et al.*, 2017; Singh *et al.*, 2019; Naresh *et al.*, 2020
Maize-based diversification	Maize → Potato → Onion	14.5	1.73	1.10	62	+0.15	330	Higher income and risk diversification	Jat *et al.*, 2015; Parihar *et al.*, 2018; Naresh *et al.*, 2021
Cereal-Legume-Oilseed	Pearl millet → Chickpea → Mustard	11.2	1.88	0.92	65	+0.18	310	Improved soil fertility and stability	Ramesh *et al.*, 2014; Sharma *et al.*, 2020; Naresh *et al.*, 2019
Cereal-Pulse intercropping	Sorghum + Pigeonpea (2:1)	8.6	1.94	0.85	68	+0.20	300	Yield stability under climate stress	Willey, 1979; Ghosh *et al.*, 2006; Naresh *et al.*, 2017
Integrated crop-livestock	Rice-Wheat + fodder + dairy	12.0	1.73	0.88	60	+0.22	290	Nutrient recycling and income buffering	Herrero *et al.*, 2010; Singh *et al.*, 2021; Naresh *et al.*, 2022
Agroforestry-based system	Wheat + Poplar(boundary/strip)	13.5	1.82	0.95	63	+0.30	260	Carbonsequestration and microclimate regulation	Nair, 2011;Dhyani *et al.*, 2016; Naresh *et al.*, 2023

Soil Health and Biological Functioning

Soil health and biological functioning are increasingly recognized as central to rebuilding ecological resilience in agroecosystems, particularly under crop diversification strategies. Diversified cropping systems, including rotations, intercropping, and inclusion of legumes and cover crops, enhance soil organic carbon dynamics, microbial biomass, and functional diversity, which collectively improve nutrient cycling and stress buffering capacity of soils (Lal, 2020; Smith *et al.*, 2023) [32, 55]. However, crop diversification alters the quantity and quality of root exudates and residue inputs, thereby stimulating beneficial microbial communities involved in nitrogen fixation, phosphorus solubilization, and suppression of soil-borne pathogens (Venter *et al.*, 2022) [58]. These biologically mediated processes strengthen soil structure, aggregate stability, and water infiltration, which are critical for resilience under increasing climate variability.

Biological functioning under diversified systems is closely linked with trophic interactions in the soil food web. Greater plant diversity supports a wider range of microorganisms, mesofauna, and macrofauna, enhancing enzymatic activities and improving nutrient use efficiency (Bender *et al.*, 2016) [4]. Moreover, conservation agriculture-based diversification in the Indo-Gangetic Plains shows that diversified rotations combined with residue retention significantly improve soil carbon sequestration, microbial activity, and long-term productivity compared to cereal mono-cropping (Naresh *et al.*, 2021) [38]. Such improvements contribute to ecological resilience by increasing the soil's capacity to recover from disturbances such as drought, heat stress, and nutrient shocks. Therefore, diversified cropping systems reduce dependency on external inputs by enhancing internal biological regulation mechanisms, thereby supporting sustainable intensification goals (Pretty *et al.*, 2018; Tamburini *et al.*, 2020) [45, 56].

Table 8: Soil Health, Biological Functioning, and Ecological Resilience under Crop Diversification

Soil Health Indicator	Crop Diversification Approach	Biological Mechanism	Quantitative Improvement Observed*	Ecological Significance	Scientist & Year
Soil organic carbon	Cereal-legume rotations, cover crops	Increased residue input, microbial C stabilization	SOC ↑ 0.2-0.6 Mg C ha-1yr-1	Enhanced carbon sequestration and climate resilience	Lal (2020); Smith *et al.* (2023)
Microbial biomass carbon	Intercropping, diversified rotations	Root exudate diversity, microbial proliferation	MBC ↑ 20-45%	Improved nutrient cycling and soil buffering capacity	Venter *et al.* (2022)
Enzyme activity (dehydrogenase, phosphatase)	Multi-crop sequences	Accelerated SOM mineralization	Enzyme activity ↑ 25-60%	Faster nutrient availability and soil recovery	Jat *et al.* (2021)
Nitrogen availability	Legume inclusion	Biological N fixation, microbial N turnover	Available N ↑ 15-35 kg ha-1	Reduced fertilizer dependency	Bender *et al.* (2016); Tamburini *et al.* (2020)
Soil aggregation	Residue-retained diversified systems	Fungal hyphae binding, SOC-mediatedaggregation	Macro-aggregates ↑ 10-30%	Improved aeration and erosion resistance	Smith *et al.* (2023)

Water infiltration	Crop rotation + residues	Improved pore continuity	Infiltration rate ↑ 20-50%	Drought resilience and reduced runoff	Pretty *et al.* (2018)
Soil carbon sequestration	Conservation agriculture with diversification	Reduced C loss, microbial stabilization	C sequestration ↑ 0.3-0.8 Mg ha-1yr-1	Long-term soil fertility and resilience	Naresh *et al.* (2018)
Soil biological resilience	Cereal-legume-oilseed systems	Functional redundancy of soil biota	Yield stability ↑ 15-25% under stress	Faster recovery from heat and moisture stress	Naresh *et al.* (2021)

System Productivity and Profitability

Crop diversification has demonstrated clear gains in system productivity and farm profitability while simultaneously rebuilding ecological resilience across diverse agro-ecosystems. However, replacing cereal-cereal monocropping with diversified rotations involving pulses, oilseeds, vegetables, or fodder crops increases overall system productivity by 10-25% due to better resource-use efficiency and complementary growth patterns (Kumar *et al.*, 2021; Naresh *et al.*, 2022) [39, 43]. Inclusion of legumes enhances biological nitrogen fixation, leading to improved soil nutrient availability and reduced dependence on synthetic fertilizers, which directly lowers input costs and raises net returns. Studies from the Indo-Gangetic Plains reported 15-30% higher net profitability in diversified systems compared with continuous rice-wheat systems, even under variable climatic conditions (Singh *et al.*, 2020; Jat *et al.*, 2023) [52, 17]. Beyond yield and income, diversified cropping systems significantly strengthen ecological resilience. However, results indicate improvements in soil organic carbon, microbial biomass, and aggregate stability within 3-years of diversification, enhancing the soil's capacity to retain water and nutrients (Lal, 2020; Sharma *et al.*, 2022) [32, 49]. These changes translate into greater yield stability during droughts or excessive rainfall, reducing production risk for farmers. Diversification also disrupts pest and disease cycles, lowering pesticide use by 20-40% in many multi-crop systems and contributing to higher benefit-cost ratios (Tilman *et al.*, 2020) [57]. Moreover, diversified systems provide multiple income streams, buffering farmers against market and climate shocks. Integration of high-value crops and short-duration legumes increases cropping intensity and labor productivity while promoting biodiversity at field and landscape scales (Pretty *et al.*, 2018; Jat *et al.*, 2023) [45, 17]. Therefore, crop diversification is not merely an ecological intervention but a viable profitability-enhancing strategy that aligns economic sustainability with long-term resilience of agro-ecosystems.

Table 9: Effects of Crop Diversification on Productivity, Profitability, and Ecological Resilience

Parameter	Cropping System Comparison	Observed Impact (Range/Change)	Key Ecological/Economic Explanation	Scientist & Year
System productivity	Cereal-cereal vs. cereal-legume / oilseed rotations	+10-25% system productivity	Improved resource-use efficiency and niche complementarily	Kumar *et al.* (2021); Jat *et al.* (2023)
Grain-equivalent yield	Rice-wheat vs. diversified rotations	+0.6-1.2 t ha-1	Better nutrient cycling and reduced yield penalties under stress	Singh *et al.* (2020)
Net farm profitability	Monocropping vs. diversified systems	+15-30% higher net returns	Reduced fertilizer and pesticide costs; diversified market income	Naresh *et al.* (2022); Jat *et al.* (2023)
Benefit-cost ratio	Cereal monoculture vs. multi-crop systems	Increased from 1.5-1.8 to 2.0-2.4	Lower input dependency and higher yield stability	Sharma *et al.* (2022)
Soil organic carbon	Continuous cereals vs. diversified cropping	+0.2-0.4% SOC within 3-5 years	Residue diversity and enhanced microbial activity	Lal (2020)
Soil biological health	Low-diversity vs. high-diversity systems	+20-35% microbial biomass	Greater carbon substrates and rhizosphere diversity	Sharma *et al.* (2022)
Pest and disease incidence	Monocropping vs. diversified systems	-20-40% pesticide use	Disruption of pest life cycles and increased natural enemies	Tilman *et al.* (2020)
Yield stability under climate stress	Uniform systems vs. diversified systems	Reduced yield variability by 15-25%	Improved soil moisture retention and resilience	Pretty *et al.* (2018)

4. Artificial Intelligence: Enabling Precision and System Intelligence: AI in Agricultural Decision-Making

AI-enabled decision systems significantly improve precision and systems intelligence in rice-wheat cropping systems and diversification planning. Khan *et al.* (2025) [27] demonstrated that convolutional neural networks integrated with explainable AI tools achieved high accuracy in rice disease identification and varietal classification, with feature-attribution analysis revealing that spectral reflectance and canopy texture were dominant predictors. These results indicate that AI enhances both diagnostic reliability and interpretability, which is essential for operational decision-making in intensive rice systems.

Li *et al.* (2024) [33] reported that in wheat machine-learning models combining satellite imagery, weather variables, and management data improved yield prediction accuracy (R^2>0.85) compared with traditional statistical models. Moreover, AI effectively captures spatial-temporal variability, enabling refined recommendations for irrigation and nutrient management under diverse agro-ecological conditions. Sharma *et al.* (2023)[47, 48] found that deep learning-based disease surveillance reduced detection lag for rust and blight, thereby minimizing yield losses and stabilizing productivity in rice-wheat rotations.

Pandey *et al.* (2024) [44] showed that AI-driven crop recommendation systems integrating soil health indicators and climate projections improved the selection of alternative crops such as pulses and oilseeds, enhancing system resilience and profitability beyond rice-wheat monoculture. Naresh *et al.* (2024) [42] reported that AI-supported precision tools, including variable-rate nutrient application and sensorbased monitoring, improved nutrient-use efficiency and reduced input costs while maintaining yields in diversified cropping systems. However, AI strengthens data-driven decision-making, enabling sustainable intensification and informed diversification in rice-wheat systems.

Precision Water and Nutrient Management

Precision water and nutrient management markedly improves crop productivity, resource-use efficiency, and economic returns in the NWIGP. Pratap *et al.* (2022) reported that zero-till DSR increased water productivity by 8-10% while reducing nitrogen inputs by approximately 32 kg ha^{-1}, without any reduction in grain yield. This indicates that aligning nitrogen and water application with real-time crop demand not only enhances efficiency but also reduces input wastage and environmental impact. Similarly, in wheat,

Dass *et al.* (2025) found that double zero-till wheat managed with irrigation scheduled at 25% depletion of available soil moisture and precision nitrogen application increased grain yields by 6-10% and improved photosynthetic efficiency and recorded reductions in nitrous oxide emissions, demonstrating that integrated water and nutrient management can simultaneously improve productivity and environmental sustainability.

Optimized irrigation regimes and tillage strategies significantly lowered the water footprint of rice systems, enhanced nutrient-use efficiency, and improved grain quality, particularly under water-limited conditions. When combined with crop diversification strategies, such as replacing rice with maize or legumes within precision-managed systems, overall system water and nitrogen efficiency improved further, while maintaining high productivity and profitability (Gupta *et al.* 2023) [15]. However, the integration of AI-enabled decision support, sensor-guided nitrogen management, and precise irrigation scheduling facilitates the redesign of rice-wheat systems. These approaches improve yields, reduce input requirements, enhance resource-use efficiency, and support diversification, providing a sustainable pathway for intensification of cereal-based cropping systems in the NW IGP.

Yield Prediction and Risk Management

Artificial intelligence (AI), when integrated with precision land and system management significantly improves yield predictability and resource-use efficiency in rice-wheat systems. De Clercq and Mahdi (2024) [9] reported that machine-learning models such as CatBoost and LightGBM explained up to 82% of spatial and temporal rice yield variability across India, enabling reliable early-season yield forecasts. Their explainable AI analysis identified temperature, soil moisture, and leaf area index as dominant yield drivers, highlighting the role of AI in proactive irrigation and nutrient management. Similarly, Sah *et al.* (2024) [46] showed that integrating SAR and optical remote-sensing data in ML frameworks substantially reduced spatial uncertainty in rice yield prediction across diverse agro-ecologies.

In wheat, Yang *et al.* (2025) [59] demonstrated that UAV-based multisensor data combined with deep-learning models achieved prediction accuracies exceeding R^2 0.73 under variable nitrogen regimes, enabling early detection of stress and more precise nitrogen management. These findings indicate that AI-based yield prediction is most effective when crop growth variability can be accurately captured and interpreted in real time.

Precision laser land leveling (LLL) has been shown to provide the physical basis for effective AI deployment. Naresh *et al.* (2013) [34] in the western Indo-Gangetic Plains revealed that LLL increased rice and wheat yields by 6-11%, improved water-use efficiency by up to 48%, and reduced irrigation time and energy consumption. Jat *et al.* (2015) [20] demonstrated that LLL combined with conservation agriculture saved 20-30% irrigation water and improved yield stability, confirming its role as a precursor technology for precision and intelligent farming systems. Gupta *et al.* (2023) [15] found that maize-wheat diversification with precision irrigation and nitrogen management improved water and nitrogen use efficiency by 15-25% while reducing yield losses under heat stress. Jat *et al.* (2024) [24] reported that substituting rice with maize or legumes increased overall system productivity by 10-20% and reduced climatic vulnerability.

Table 10: Artificial Intelligence in yield prediction and resource-management outcomes in redesigned rice-wheat systems

Scientist & Year	Crop / system	Technology / approach used	Key quantitative outcomes	Resource & risk management implications
De Clercq & Mahdi (2024)	Rice yield prediction	ML models (CatBoost, LightGBM) using 20-yr climate + satellite data	R^2 up to 0.82, MAPE ~0.16; strong early-season yield predictability	AI models reduce yield uncertainty and enable advance irrigation and fertilizer planning
Sah, Haldar & Singh (2024)	Spatial rice yield variability	SAR + optical remote sensing with ML	Improved spatial accuracy across agro-ecologies	Multi-source data fusion enhances robustness of AI forecasts
Yang *et al.* (2025)	Wheat yield estimation	UAV multisensor data + ensemble ML / deep learning	R^2 ~0.73-0.78 depending on sensor fusion	Sensor integration improves yield discrimination under N stress
Naresh *et al.* (2013)	Rice-wheat system, western UP	Laser land leveling (LLL)	Rice & wheat yield ↑ 6-11%; water use efficiency ↑ up to 48%; irrigation time ↓	Precision land surface improves uniform water/nutrient distribution and lowers production risk
Jat *et al.* (2015)	Irrigated rice-wheat ecosystem	LLL + conservation agriculture	Yield gains 7-12%; water savings 20-30%; energy savings significant	LLL is a precursor technology enabling precision input management
Gupta *et al.* (2023)	Maize-wheat diversification	Precision irrigation + N optimization	Water & N use efficiency ↑ 15-25%; stable yields under heat stress	Diversification reduces climatic risk compared to continuous rice
Singh *et al.* (2023)	System productivity	Precision land leveling	Wheat-equivalent yield ↑ 6-11%; water productivity ↑ 30%	Improved field uniformity stabilizes yields in variable seasons
Jat *et al.* (2024)	Rice substitution & diversification	Maize/legume-based rotations	System productivity ↑ 10-20%; reduced terminal heat stress	Diversification enhances resilience and sustainability of RW systems

Integration with LLL and Diversification

North-western Indo-Gangetic Plains (NWIGP) indicate that the integration of laser land leveling (LLL) with crop diversification, strengthened by artificial intelligence (AI)-enabled system intelligence, has significantly redesigned the rice-wheat system toward higher efficiency and resilience. Jat *et al.* (2019) [22] and Humphreys *et al.* (2020) [16] showed that LLL improved field uniformity, resulting in 20-30% irrigation water savings and 8-12% yield gains in rice and wheat. Naresh *et al.* (2021) [38] demonstrated that uniform moisture distribution under LLL enhanced nutrient uptake efficiency and reduced yield variability across farms. When AI-driven decision support systems using satellite data, soil sensors, and crop growth models were integrated, Sidhu *et al.* (2021)[50] reported 15-25% reductions in nitrogen fertilizer use without yield penalties, indicating improved synchronization between crop demand and input supply.

Gathala *et al.* (2022) [13] and Naresh *et al.* (2022) [39, 43] highlighted that inclusion of maize, pulses, and oilseeds in place of continuous rice reduced irrigation demand and improved soil physical health, particularly under LLL-managed fields. AI-enabled system intelligence helped identify location-specific diversification pathways by analyzing soil texture, groundwater status, and climate risk, leading to higher system stability (Sharma *et al.*, 2023)[47, 48]. On-farm assessments showed that diversified systems supported by AI analytics achieved 18-35% higher net returns and over 40% improvement in water productivity, while also lowering exposure to heat stress and erratic rainfall (Jat *et al.*, 2024; Naresh *et al.*, 2023) [24, 25, 40, 41]. However, convergence of LLL, diversification, and AI-based system intelligence has shifted the rice-wheat system in the NW IGP from input-intensive management toward data-driven, climate-smart, and sustainable intensification.

Table 11: Effects of Laser Land Leveling, Diversification, and AI-Enabled System Intelligence on Rice- Wheat System in NW IGP

Scientist(s) & Year	Intervention / Technology	Cropping System Context	Key quantitative outcomes	System-Level Implications
Jat *et al.*, 2019	Laser land leveling (LLL)	Rice-wheat	20-30% irrigation water saving; 8-12% yield increase	Improved water productivity and uniform crop establishment
Humphreys *et al.*, 2020	LLL + precision irrigation	Rice-wheat	Water productivity increased by ~25%; reduced irrigation time	Groundwater conservation in NW IGP
Naresh *et al.*, 2021	LLL + precision nutrient management	Rice-wheat	15-20% higher nutrient-use efficiency; stable yields	Reduced input losses and spatial yield variability
Sidhu *et al.*, 2021	AI-based DSS (remote sensing, sensors)	Rice-wheat	15-25% reduction in N fertilizer without yield loss	Data-driven nutrient synchronization
Gathala *et al.*, 2022	Diversification under CA & LLL	Rice-maize/pulses-wheat	>40% increase in water productivity; improved soil health	Reduced dependence on puddled rice
Naresh *et al.*, 2022	Crop diversification + LLL	Rice-wheat alternatives	Higher net returns (18-30%); lower irrigation demand	Enhanced system profitability and resilience
Sharma *et al.*, 2023	AI-enabled system intelligence (ML, climate data)	Diversified RW systems	Improved crop choice accuracy; reduced climate risk	Adaptive, climate-resilient decision-making
Naresh *et al.*, 2023	AI-driven advisory platforms	Rice-based systems	Improved input-use efficiency; reduced yield variability	Transition to smart, climate-smart farming
Jat *et al.*, 2024	Digital & AI-integrated CA systems	Rice-wheat & diversified systems	18-35% higher system profitability; stable yields under stress	Sustainable intensification at system scale

Conclusions

The redesign of the rice-wheat production system in the North-Western Indo-Gangetic Plains (NW IGP) through laser land leveling, crop diversification, and artificial intelligence (AI) represents a strategic transition toward sustainable, resilient, and resource-efficient agriculture. Although the rice-wheat system has been central to regional food security, its long-term intensification has resulted in groundwater depletion, soil structural degradation, declining input-use efficiency, and increased vulnerability to climate variability, as acknowledged by Ladha *et al.* (2003), Gupta *et al.* (2012), and Jat *et al.* (2014)[64]. These interlinked challenges highlight the need for holistic system redesign rather than isolated technological interventions.

Laser land leveling forms the physical foundation of this transformation by improving field uniformity and enabling precise water and nutrient management. Its integration enhances irrigation efficiency, reduces energy consumption, and stabilizes crop establishment, thereby improving productivity and profitability.

Beyond immediate agronomic benefits, precision land leveling supports conservation-oriented practices by facilitating timely operations, uniform residue management, and efficient input distribution. In the NW IGP context, these cumulative gains contribute significantly to long-term water conservation and sustainable intensification, as emphasized by Naresh *et al.* (2018) [36] and Aryal *et al.* (2015) [1].

Crop diversification further strengthens system resilience by reducing reliance on water-intensive rice and improving ecological balance. Diversified rotations incorporating pulses, oilseeds, or alternative cereals enhance soil health, nutrient cycling, and biological activity while lowering production risks and environmental footprints. Such systems improve farm income stability and align with broader objectives of climate adaptation and nutritional security. The integration of diversified cropping with precision land management has been recognized as a key pathway for improving system sustainability in the NW IGP by Gathala *et al.* (2013)[65], Jat *et al.* (2019) [22], and Sapkota *et al.* (2015)[66].

The incorporation of artificial intelligence adds a critical decision-support layer that enables data-driven, site-specific, and adaptive management. AI-based tools integrate information on soil variability, weather dynamics, and crop performance to optimize irrigation scheduling, fertilizer application, and crop choice. When embedded within leveled fields and diversified cropping systems, AI enhances precision, reduces resource wastage, and improves farmers' capacity to manage climatic and market uncertainties, thereby strengthening system resilience (Kamilaris and Prenafeta-Boldú, 2018).

Therefore, synergistic integration of laser land leveling, crop diversification and AI provides a comprehensive framework for redesigning the rice-wheat system of the NW IGP. Scaling this integrated approach will require supportive policies, institutional strengthening, capacity building, and accessible extension services. Such a transformation is essential for sustaining productivity, conserving natural resources, enhancing farmer livelihoods, and ensuring long-term food and environmental security in the region.

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