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Impact of irrigation, fertilizer, and pesticide management practices on groundwater and soil health in the rice–wheat cropping system—a comparison of conventional, resource conservation technologies and conservation agriculture

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Abstract

Agricultural intensification in the Northwestern Indo-Gangetic Plain (NWIGP), a critical food bowl supporting millions of people, is leading to groundwater depletion and soil health degradation. This is primarily driven by conventional cultivation practices in the rice–wheat (RW) cropping system, which dominates over 85% of the IGP. Therefore, this study presents a systematic literature review of input management in the RW system, analyzes district-wise trends, outlines the current status, identifies problems, and proposes sustainable management options to achieve development goals. Our district-wise analysis estimates potential water savings from 20 to 60% by transitioning from flood to drip, sprinkler, laser land leveling, or conservation agriculture (CA). Alongside integrating water-saving technologies with CA, crop switching and recharge infrastructure enhancements are needed for groundwater sustainability. Furthermore, non-adherence with recommended fertilizer and pesticide practices, coupled with residue burning, adversely affects soil health and water quality. CA practices have demonstrated substantial benefits, including increased soil permeability (up to 51%), improved organic carbon content (up to 38%), higher nitrifying bacteria populations (up to 73%), enhanced dehydrogenase activities (up to 70%), and increased arbuscular mycorrhizal fungi populations (up to 56%). The detection of multiple fertilizers and pesticides in groundwater underscores the need for legislative measures and the promotion of sustainable farming practices similar to European Union strategies. Lastly, emphasis should be placed on fostering shifts in farmers' perceptions toward optimizing input utilization. The policy implications of this study extend beyond the NWIGP region to the entire country, stressing the critical importance of proactive measures to increase environmental sustainability.

Keywords Irrigation · Nutrient · Pesticide · Soil health · Groundwater · Agricultural sustainability · Environmental pollution

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Abbreviations

BISA	Borlaug Institute for South Asia
CA	Conservation agriculture
CCSHAU	Chaudhary Charan Singh Haryana Agricultural University
CGWB	Central ground water board
CSAP	Climate-smart agricultural practices
CSSRI	Central Soil Salinity Research Institute
CT	Conventional practice
DAP	Di-ammonium phosphate
DAS	Days after sowing
DI	Drip irrigation
DSR	Dry direct seeded rice
FI	Flood irrigation

GDP	Gross domestic product
GW	Groundwater
IARI	Indian Agricultural Research Institute
ICAR	Indian Council of Agricultural Research
IIFSR	Indian Institute of Farming Systems Research
IIMR	Indian Institute of Maize Research
LLL	Laser land leveling
MOP	Muriate of potash
MSP	Minimum support price
MW	Maize-wheat
NPK	Nitrogen phosphorus potassium
NUE	Nutrient use efficiency
NWIGP	Northwestern Indo-Gangetic plain
PAU	Punjab Agricultural University
PIM	Participatory irrigation management
PPP	Public-private partnerships
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
PTR	Puddled transplanted rice
RW	Rice-wheat
SLR	Systematic literature review
SOC	Soil organic carbon
SPAD	Soil plant analysis development
SSDI	Sub-surface drip irrigation
SSNM	Site-specific nutrient management
STCR	Soil-test crop response
UP	Uttar Pradesh
WUE	Water use efficiency
ZT	Zero tillage
@	At a rate of

Introduction

The global crisis of hunger and malnutrition is continuing, with an estimated 900 million people experiencing severe food insecurity in 2023 (FAO 2022). This represents a stark increase of 225 million people compared to the pre-COVID-19 levels, highlighting pressing concerns for food security. Moreover, by 2050, 9.8 billion people are anticipated to live on the earth (UN 2022), necessitating increased food production by either expanding agricultural land or enhancing productivity (Fagodiya et al. 2023). However, the extent of agricultural land has declined by 134 million hectares (Mha) between 2000 and 2020, equivalent to the size of Peru (FAO 2022). Yet, the primary crop production has increased by 52% during the same period, mainly due to intensified use of inputs such as irrigation, fertilizers, and pesticides (FAO 2022). The Indo-Gangetic Plain (IGP) in South Asia witnessed the advent of the green revolution, resulting in a doubling of rice and wheat yields due to a significant increase in pesticide usage by 375-fold, fertilizer

application by sevenfold, and expansion of irrigated land by twofold (Oerke 2006).

The rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system (RW) holds immense importance in ensuring food security, generating employment, and sustaining the livelihoods of millions of people across South Asia's 13.5 Mha of agricultural land (Jat et al. 2020; Sharma et al. 2021; Thind et al. 2023). RW is India's most important cropping system, covering around 10.0 Mha, primarily in the IGP (Rana et al. 2022). It contributes to approximately half of the national production of rice and three-fourths of the production of wheat (Dhillon et al. 2010). In the Northwestern Indo-Gangetic Plain (NWIGP), the prevailing production system is dominated by the RW system, supported by skewed policies such as free electricity and heavily subsidized agrochemicals, leading to escalated groundwater extraction and the indiscriminate application of fertilizers and pesticides (Chakraborti et al. 2023). The persistent cultivation of less water-, time-, labor-, cost-, and energy-efficient RW cropping systems, coupled with the adverse impacts of crop residue burning for more than four decades has led to numerous interrelated and complex environmental challenges (Saharawat et al. 2010; Singh et al. 2022b). These include a declining groundwater table (Devineni et al. 2022; Joseph et al. 2022), soil health degradation characterized by loss of fertility and biodiversity (Sapkota et al. 2017; Parihar et al. 2020), increasing environmental pollution, exacerbated farm labor scarcity (Humphreys et al. 2010), declining productivity (Gora et al. 2022), and a looming threat to ecosystem sustainability (Singh et al. 2022b). Therefore, these multifaceted issues provide a robust need for the adoption of conservation agricultural practices (Sapkota et al. 2017; Fagodiya et al. 2023).

Conservation agriculture (CA) is considered a sustainable approach for enhancing water and nutrient use efficiency, and improving crop productivity while restoring soil health (Bhattacharyya et al. 2015). CA is guided by three fundamental principles: (i) reduced or zero tillage (ZT) for minimum soil disturbance, (ii) maximum crop cover or crop residue retention, and (iii) diversification of crops (FAO 2023). Numerous studies conducted in the NWIGP have underscored the potential of CA-based practices in resource conservation, enhancing water productivity, and rejuvenating soil health within the RW system (Das et al. 2013; Singh et al. 2022b). The adoption of CA practices has been associated with substantial improvements in soil structure and aggregate stability (Modak et al. 2020), improved macro- and micro-nutrient availability (Jat et al. 2019b), improved soil microbial diversity and enzymatic activities through increased soil organic carbon (Parihar et al. 2020; Das et al. 2023), suppress of soil evaporation, and attenuation of soil temperature and moisture variability (Singh and Sidhu 2014), reduced air pollution from stubble burning

(Jain et al. 2018), and improved the overall physical, chemical, and biological properties of soils (Jat et al. 2019a).

About 90% of consumptive water usage worldwide and 70% of freshwater withdrawals are driven by agriculture, a significant contributor to global freshwater scarcity (Fishman et al. 2015). Moreover, the global land area equipped for irrigation has more than doubled (349 Mha) since the 1960s, with a sizable share (70%) in Asia (FAO 2022). India stands as the largest global user of groundwater (GW; Joseph et al. 2022), extracting more than China and the United States combined. In NWIGP, GW tables have incessantly been declining at alarming rates, ranging between 0.2 and 1.5 m/year (Humphreys et al. 2010). Moreover, some projections show if the mitigation efforts are not made then the groundwater depletion rates could be as high as 2.8 m/year in certain areas by 2028 (Shekhar et al. 2020). The RW system's substantial reliance on groundwater for irrigation is often blamed for over-exploitation, raising concerns about the sustainability of current agricultural practices. Thus, water-saving technologies must be adopted to increase water productivity (crop yield per unit of water consumption) while sustaining GW levels and ensuring farming profitability. Water-saving technologies such as micro-irrigation (drip irrigation and sprinkler) and laser land leveling (LLL) demonstrated their effectiveness in field situations (Suren-dran et al. 2021; Brar et al. 2022). Most existing studies have assessed the effectiveness of resource conservation technologies (RCT) at the field level, focusing on one technology at a time (Devineni et al. 2022; Chakraborti et al. 2023). They have not explored the potential of transitioning to CA-based rice–wheat systems and the combined effects of multiple conservation practices on sustainably managing scarce groundwater resources and their synergistic impact on regional ecological issues. Therefore, the lessons learned and insight generated from such small-scale studies could not attract the required attention of the policymakers as policies are often designed and implemented at a large scale, i.e., at the district level (unit of administration) in India. To bridge this gap and support effective, evidence-based policy communication, this study assesses and compares the effects of conventional practices versus RCT and CA on GW savings in NWIGP districts, providing actionable insights for stakeholders involved in promoting and implementing conservation programs.

Pesticides and fertilizers are integral components of modern agriculture, applied to manage pests and enhance crop productivity (Baweja et al. 2020). In India, fertilizer consumption surged to 32.5 million metric tons (Mt) in 2020, marking a significant 95% increase since 2000, while pesticide usage increased by 37% to 0.450 Mt over the same period (FAO 2022). However, the continuous and excessive use of chemical fertilizers and pesticides has led to a range of soil and environmental challenges. Excessive fertilizer

usage leads to biological, chemical, and physical soil degradation, including soil compaction, acidification, nitrogen leaching, decreased soil organic carbon, and shift of microbial populations (Mari et al. 2008; Guo et al. 2010; Rahman and Zhang 2018). Similarly, pesticides, owing to their xenobiotic properties, may adversely impact enzyme activities and beneficial soil microorganisms, notably nitrogen-fixing and phosphorus-solubilizing organisms, as well as essential symbionts (Fox et al. 2007; Kalia and Gosa 2011; Wu et al. 2021). Additionally, studies reported elevated nitrate (NO_3^-) levels and pesticide contamination in groundwater in certain regions of the IGP (Saha and Alam 2014; Singh et al. 2022a). The presence of pesticides in crops, stemming from pesticide residues in the soil and their uptake through contaminated groundwater used for irrigation, poses a hazardous threat to both soil health and crop quality (Hossain et al. 2022). Despite this, research on the impact of agrochemicals, particularly pesticides, on soil health, especially soil microflora and fertility, remains limited.¹ Therefore, this study aims to assess the current status of fertilizer and pesticide management and their repercussions on soil health and groundwater resources.

NWIGP was selected as the study area because it faces significant issues, including groundwater decline, poor irrigation practices, overuse of fertilizers and pesticides, and soil health degradation. Therefore, this paper provides a comprehensive synthesis and analysis of the impact of irrigation, fertilizer, and pesticides on groundwater and soil health in Punjab, Haryana, and Uttar Pradesh. It covers (1) district-wise longitudinal trends in fertilizer consumption (1980–2020), GW levels (1996–2017), rice and wheat production (1980–2020), and soil fertility; (2) district-wise GW water-saving potential of transitioning from flood to drip irrigation, sprinkler systems, LLL, and CA; and (3) the current status of fertilizer and pesticide management and their effects on soil properties, soil microflora, fertility, and groundwater resources.

Background

Conventional rice–wheat system

The conventional practice (CT) for rice cultivation includes intensive tillage operation with two harrowing and one planking, involving both dry-tillage and wet-tillage (known as soil puddling) (Anonymous 2020). This

¹ The Scopus database searches using broad terms such as “Pesticide, AND Soil Health, AND Gangetic Plain (includes Indo-Gangetic Plain, Northwestern Gangetic Plain)” resulted in a total of 7 articles including peer-reviewed publications and conference proceedings. These 7 articles have very limited information about soil microflora.

process is followed by transplanting 25- to 30-day-old seedlings and maintaining a water depth of 2–3 inches for 30–40 days with irrigation resumed 2 days after the water recedes (Sidhu et al. 2019). This complete process is called puddled transplanted rice (PTR). Soil puddling in PTR uses up 30% of the total water in rice cultivation, consumes 11 to 28 hours ha⁻¹ time, and 2100–2400 MJ ha⁻¹ energy, depending on the level of mechanization (Verma and Dewangan 2006; Rashid et al. 2009). Puddling, in addition to reducing carbon content through increased organic matter oxidation (Sapkota et al. 2017), disrupts soil aggregates, reduces permeability in subsurface layers, and may lead to the formation of hardpans at shallow depths (Sharma et al. 2003; Kumar and Ladha 2011). Furthermore, soil puddling can negatively affect the subsequent non-rice upland crops in rotation. For example, repeated puddling operations can create anaerobic conditions, which are unfavorable for wheat cultivation as wheat requires aerobic and well-pulverized soil (Dhanda et al. 2022). In rice fields, where alternating aerobic-anaerobic conditions prevail, denitrification can result in the loss of up to 50% of the applied nitrogen (Singh and Singh 2008). Additionally, PTR practices can cause delays in wheat sowing due to limited time between rice harvest and wheat sowing, as well as farmers' preference for repeated tillage operations (an average of 5–6 ploughings) to achieve loose and friable soil with fine tilth (Biswakarma et al. 2022). Such delays in wheat planting can result in yield reductions of approximately 8–9% (Kumar and Ladha 2011). Henceforth, to facilitate the timely planting of wheat, the burning of rice residues in IGP during the winter months (October to November) has become a customary practice that adversely affects environmental and human health (Fagodiya et al. 2023). The annual crop residue production in India amounts to approximately 683 Mt, of which approximately 92 Mt is burnt in open fields, with rice and wheat collectively accounting for about 62% of the total residue burning (Jain et al. 2018).

Dry direct-seeded rice (DSR) has gained recognition as a viable alternative to PTR, as it involves sowing seeds directly in non-puddled and unsaturated soil (Rashid et al. 2009). Dry DSR offers several benefits over PTR, including labor savings of 40–45%, water savings of 30–40%, and fuel/energy savings of 60–70% (Kumar and Ladha 2011; Gathala et al. 2013; Sharda et al. 2017). Studies by Kumar and Ladha (2011) and Sharma et al. (2018) have also claimed that DSR can save 25–30% of irrigation water over PTR. These findings highlight the potential of DSR systems in conserving water resources with less cost and energy use. However, the adoption of DSR in IGP has been slow because of higher weed infestation, high incidence of iron deficiency, and lack of suitable varieties that resulted in lower rice yields (Kumar and Ladha 2011; Chauhan and Opeña 2012; Jat et al. 2020).

Trend of area, production, and yield in RW system

NWIGP, comprising Punjab, Haryana, and Western Uttar Pradesh, with a broader scope encompassing the entirety of Uttar Pradesh (UP) in this study due to India's governance structure (Fig. 1a). Over the past six decades, the RW cropping system has been the cornerstone of agricultural practices in the NWIGP. Analyzing trends from 1960 to 2020 shows the dynamic evolution of RW agricultural practices (Fig. 1d, e, f). With the advent of the Green Revolution in the late 1960s, the total RW area and production showed a staggered increase of 152% and 726% from 1960 to 2020, respectively, marked by the introduction of high-yielding crop varieties, abundant water availability, and modern agricultural techniques (Fig. 1d, e, f). The drastic expansion of RW has happened as an implication of the policy (price and institutional) supports in terms of subsidized fertilizer distribution, pricing support (MSP), and an institutional procurement system, all geared toward bolstering national food security (Handral et al. 2017). Notably, district-level analyses reveal nuanced variations, with Punjab, Haryana, and West UP witnessing significant expansions in rice cultivation, while Eastern UP experiences pronounced growth in wheat acreage (Fig. 2). Wheat is preferred in Eastern UP due to its lower irrigation requirements and assured yield (as rice yield can significantly be affected during prolonged drought spells). Furthermore, farmers in Eastern UP face considerable economic challenges compared to those in Haryana and Punjab, who rely heavily on diesel for groundwater pumping, which is relatively costly. Understanding these trends provides crucial insights for policymakers, researchers, and agricultural stakeholders to develop regional strategies for sustainable agriculture.

The trend in fertilizer consumption

India ranks among the foremost consumers of chemical fertilizers globally, trailing closely behind China in consumption volume (FAO 2022). Over the past century, fertilizer consumption patterns have undergone significant transformations across districts, reflecting evolving agricultural practices and socio-economic dynamics. Notably, from 1990 to 2020, nitrogen (N) consumption surged across almost all districts of the NWIGP, with the highest consumption rates in Punjab and Haryana (Fig. 3). Conversely, phosphorus (P) consumption trends remained relatively stable in Punjab and Haryana, with slight increments, while witnessing an uptick in UP (Fig. 3). Potassium (K) consumption exhibited a significant increase across all NWIGP districts. This shift, particularly noticeable from 2000 onwards, is due to an upsurge in P and K consumption vis-à-vis N fertilizers, propelled by government initiatives (Bora 2022). Total NPK consumption increased substantially in Punjab and Haryana

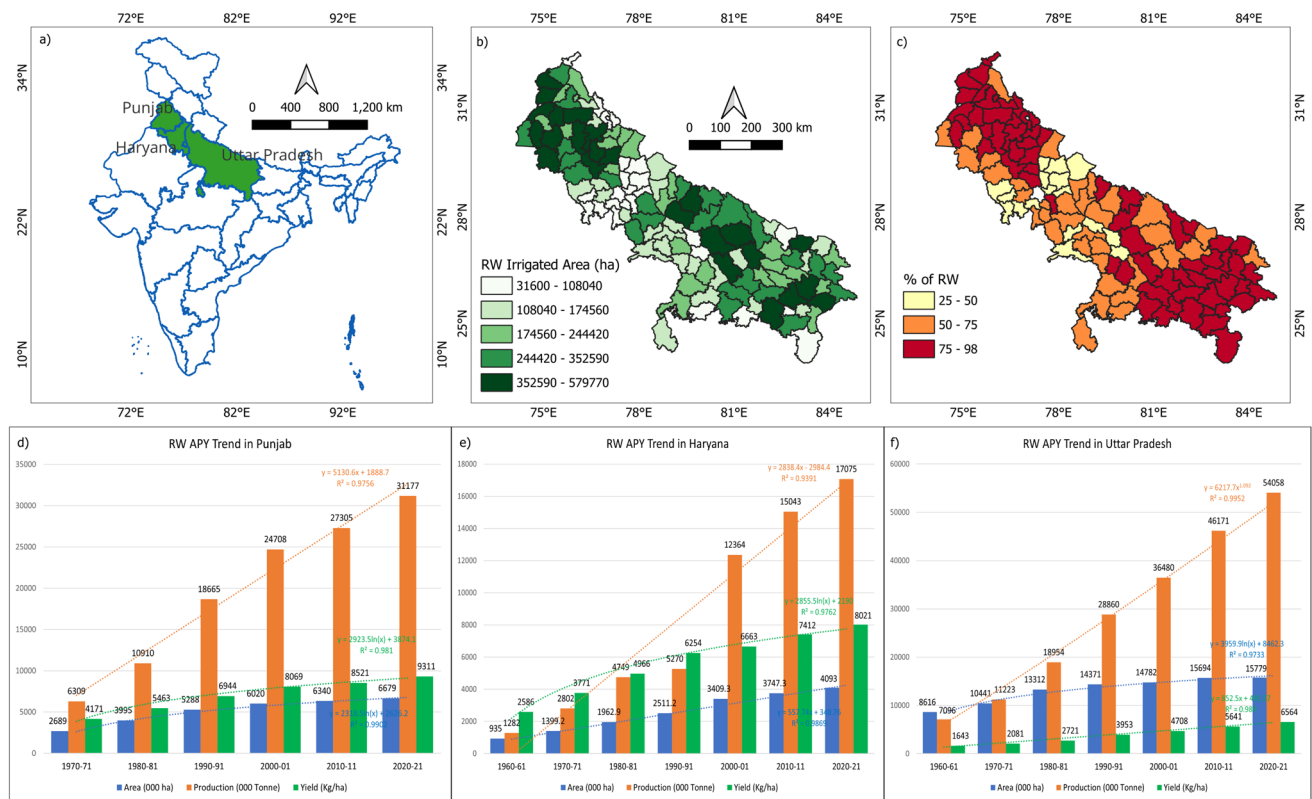


Fig. 1 Trend of area, production, and yield in rice–wheat (RW) system (**a** NWIGP in India showing three states: Punjab, Haryana, and Uttar Pradesh. **b** District-wise RW irrigated area in hectares. **c** Percentage of RW to total irrigated area. **d** RW area, production,

yield (APY) in Punjab. **e** RW APY in Haryana. **f** RW APY in Uttar Pradesh.). Source: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

from 1.076 Mt and 0.275 Mt in 1990 to 2.603 Mt (142%) and 1.280 Mt (364%) in 2020, respectively. Initially, with traditional farming methods prevailing, fertilizer consumption remained relatively modest, primarily limited to localized applications. However, with the advent of modern agricultural practices and the Green Revolution in the post-mid-twentieth century, there was a surge in fertilizer consumption due to subsidized agro-chemicals and mechanized farming techniques, especially in Punjab and Haryana. Overall, the district-wise analysis of fertilizer consumption from 1900 to 2020 provides variations in fertilizer consumption reflecting diverse agricultural landscapes, soil conditions, and management practices.

The trend of groundwater use

GW irrigation in India sustains over half of its irrigated land, contributing to 70% of agricultural output and supporting about half of the population (Fishman et al. 2015). However, rampant overuse is causing alarming groundwater table declines, potentially the world's most severe. Research by Chakraborti et al. (2023) highlights the perilous trajectory, showing decreasing rainfall trends juxtaposed

with escalating agricultural water consumption in the IGP, leading to GW depletion. We collected observed GW-level data from the Central Ground Water Board (CGWB) for both dug wells and tube wells (CGWB 2019). Dug wells, tapping shallow aquifers, can reflect changes in GW levels more quickly, reflecting localized hydrogeological conditions, while tube wells, delving deeper, provide a broader perspective on overall GW tables and can provide a more stable measure of GW levels over time.

We have prepared district-wise GW levels, particularly pre- and post-monsoon *Rabi* periods, from both dug wells and tube wells (Fig. 4). Analysis reveals widespread depletion, notably in the western regions, with some districts in Punjab and Haryana exhibiting drastic declines exceeding 10 m in dug wells and 25 m in tube wells, signaling overexploitation. Conversely, post-monsoon GW levels in Eastern UP remain relatively stable, buoyed by abundant rainfall and favorable hydrogeological conditions. However, the proliferation of tube wells in Punjab and Haryana, in contrast to Eastern UP, underscores the impact of declining groundwater tables. By dissecting district-wise data, intricate variations in GW dynamics across the NWIGP were revealed, elucidating the interplay between water demand,

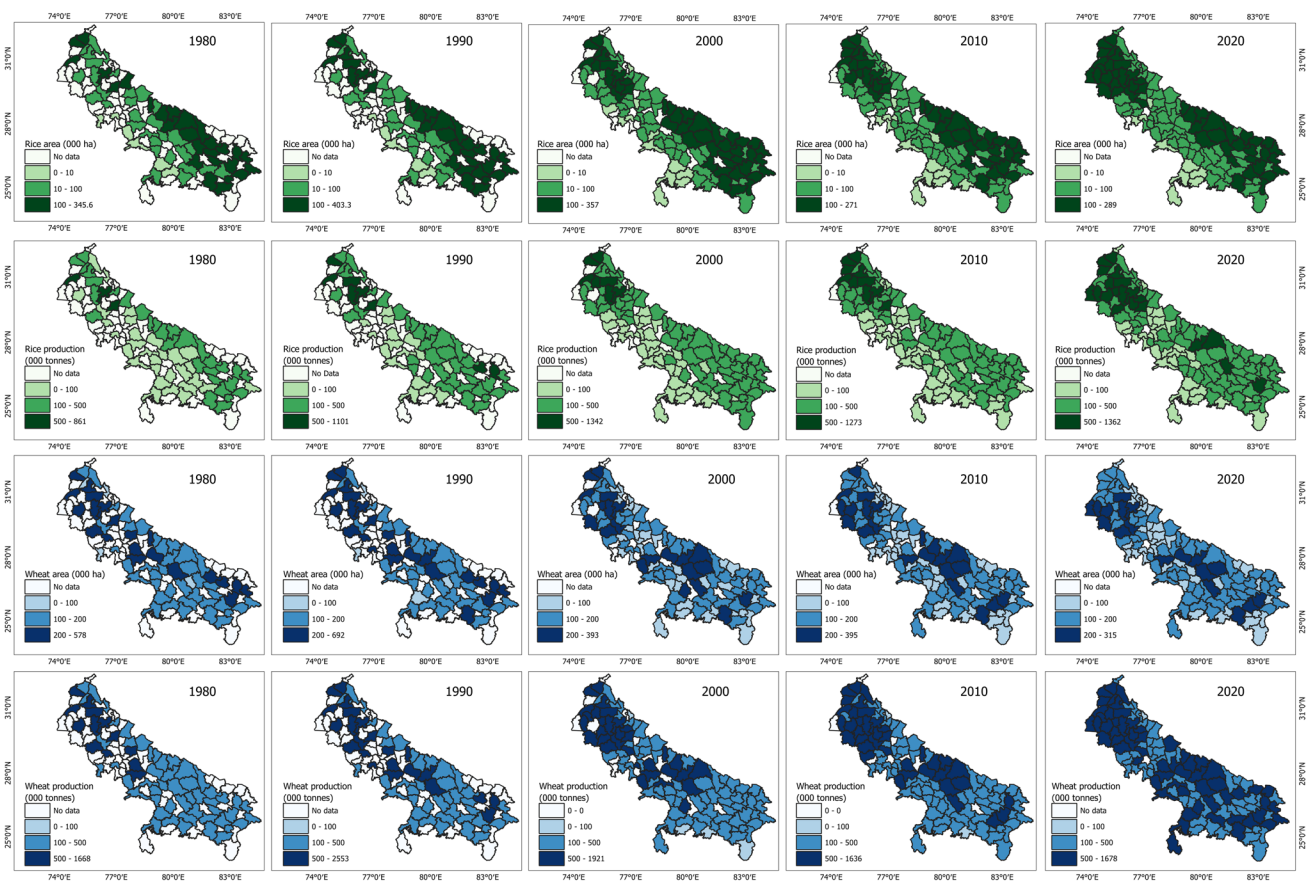


Fig. 2 District-wise area and production in NWIGP (top row, rice area in 000 hectares. second row, rice production in 000 tonnes. third row, wheat area in 000 hectares. last row, wheat production in 000

tonnes). Source: Statistical Abstract of Punjab, Haryana, and Uttar Pradesh, District-wise Crop Production Statistics, Government of India

extraction practices, and hydrogeological factors, indispensable for formulating effective strategies for sustainable GW management.

Soil fertility

Soil fertility degradation stems from the depletion of essential nutrients due to intensive crop cultivation and the widespread practice of residue burning. For instance, a RW rotation yielding 7 t ha^{-1} of rice and 4 t ha^{-1} of wheat removes over 300 kg (kg) N, 30 kg P, and 300 kg ha^{-1} K from the soil (Singh and Singh 2008). Additionally, burning crop residues leads to the loss of 80–100% of N and 20–25% of P and K present in straw (Jain et al. 2018). Pathak's (2010) analysis of soil fertility trends based on nutrient index,² reveals a

decline in P (from 1.83 in 1977 to 1.20 in 1997) and K (from 2.80 to 2.05) fertility in Haryana, while N status remains relatively constant (1.00–1.04). Conversely, Punjab exhibits an increase in N (from 1.00 to 1.67) and P (from 1.68 to 1.93) fertility, with K levels remaining stable (2.42 to 2.40) over the same period. UP, however, shows no discernible trend in NPK fertility status.

District-level soil fertility maps reveal significant deficiencies, particularly in N and P, across numerous districts (Fig. 5). N deficiency, critical for crop productivity, is widespread in the NWIGP region, with nearly all districts displaying low N stocks. Similarly, high P deficiency is observed in many areas, particularly evident in Punjab, while medium to high K availability dominates much of the NWIGP, with the highest K stocks in Punjab and Haryana. Soil nutrient deficiencies in agricultural fields stem from various factors, including inherent soil deficiencies, nutrient depletion through crop cultivation, and heavy irrigation leading to leaching and the burning of crop residue (Jat et al. 2014; Majumdar et al. 2016). External application of essential nutrients is imperative for sustaining crop productivity,

² Nutrient index = $(N_L \times 1 + N_M \times 2 + N_H \times 3) / N_T$

where N_L , N_M , and N_H are the number of samples falling in low, medium and high classes of nutrient status, respectively, and N_T is the total number of samples analyzed for a given area.

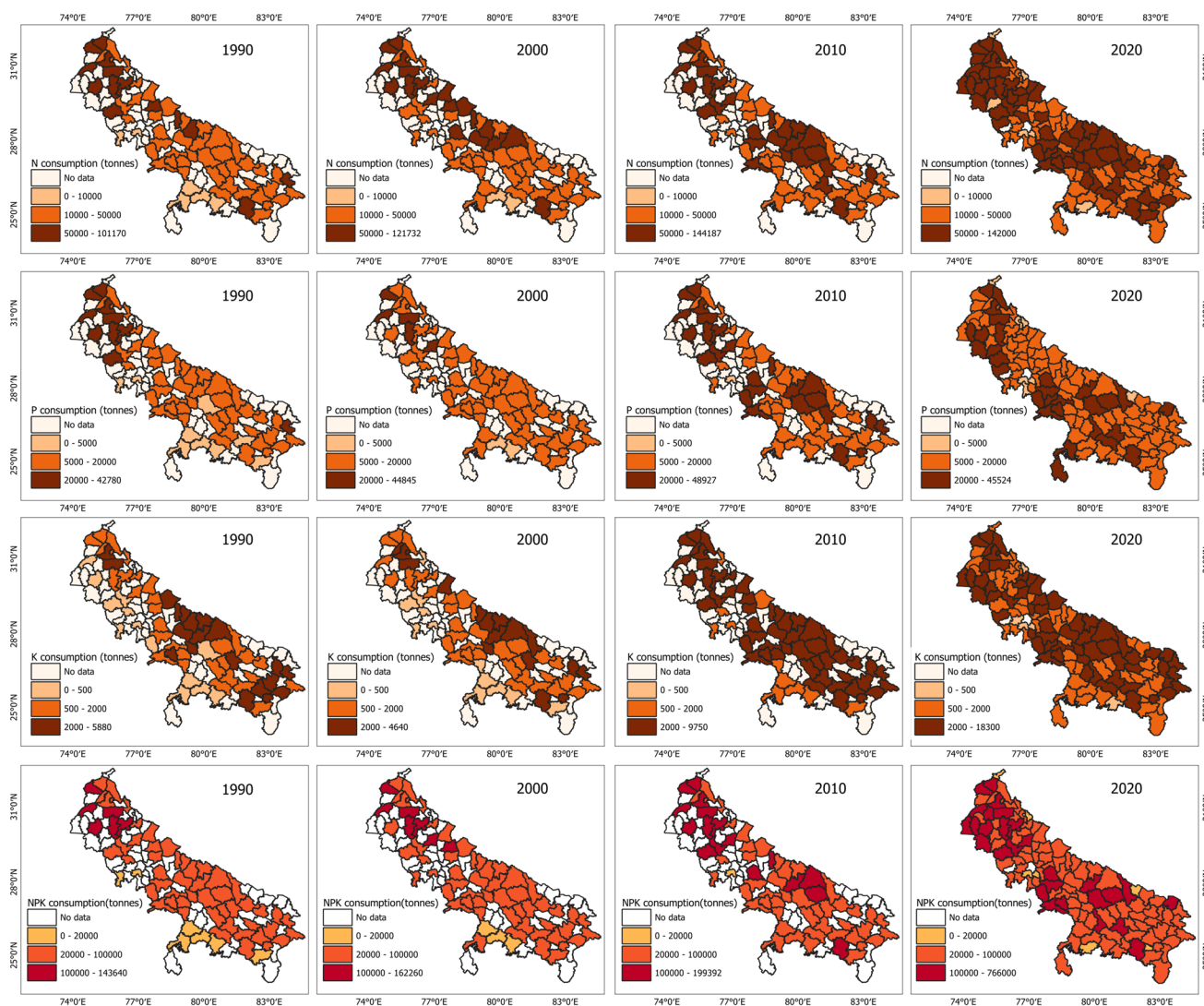


Fig. 3 District-wise fertilizer consumption in NWIGP from 1990 to 2020 (top first row, nitrogen (N) consumption in tonnes, top second row, phosphorous (P) consumption in tonnes, top third row, potas-

sium (K) consumption in tonnes, last row, NPK consumption in tonnes. Source: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

with soil-tested fertilizer application being the most suitable approach. Nonetheless, in light of limited soil testing coverage, generalized fertilizer recommendations from expert groups serve as fundamental guidelines (Bora 2022). Enhancing soil fertility understanding can help farmers to optimize crop productivity.

Pesticide consumption

Between 2000 and 2020, pesticide use in India surged by 37%, surpassing the global average increase of 30% (FAO 2022). In India, insecticides dominate pesticide consumption at 76%, followed by fungicides (13%) and herbicides (10%) (Yadav et al. 2015a). The distribution of pesticide use varies markedly across states, influenced by regional agricultural

practices and crop types. Uttar Pradesh has the highest total pesticide consumption (11,828 Mt), followed by Maharashtra (8718 Mt), Punjab (5270 Mt), and Haryana (4068 Mt) (Table 1). However, on a per hectare basis, Punjab leads with 68 kg ha⁻¹, followed closely by Haryana (64 kg ha⁻¹) and Uttar Pradesh (51 kg ha⁻¹). Furthermore, rice, the predominant crop in the NWIGP, accounts for the largest share of pesticide use at 29%, followed by cotton at 27%, vegetables at 9%, and pulses at 9% (Yadav et al. 2015a). The elevated pesticide consumption in the NWIGP necessitates in-depth research into chemicals with high acute risks and the prevalence of pesticide residues in soil and water. Furthermore, it underscores the need for farmer education programs to promote the application of recommended or optimized pesticide doses.

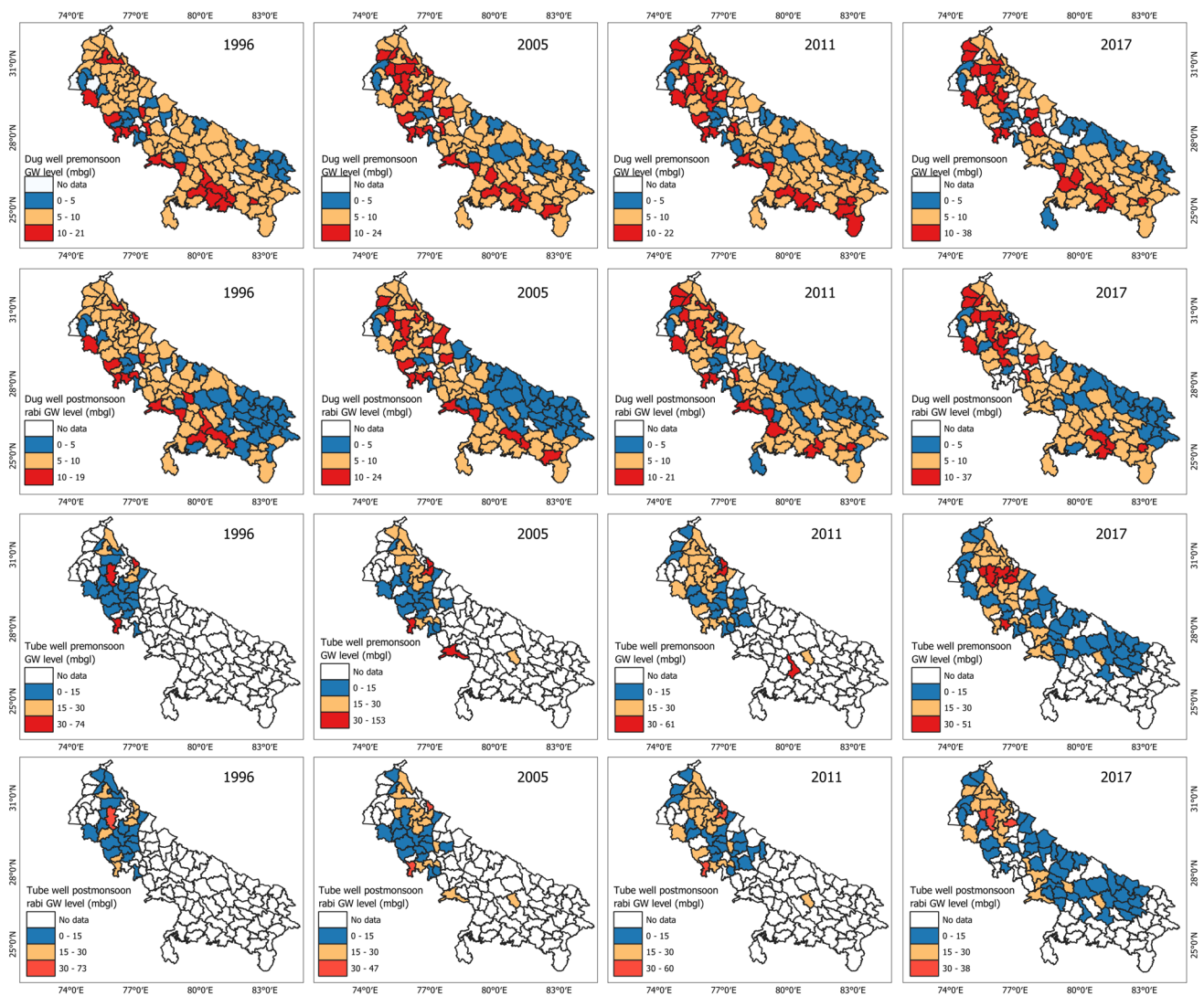


Fig. 4 District-wise groundwater levels in NWIGP from dug wells and tube wells for pre- and post-monsoon rabi season (1996–2017) (mbgl—meter below ground level). Source: Central Groundwater Board (CGWB)

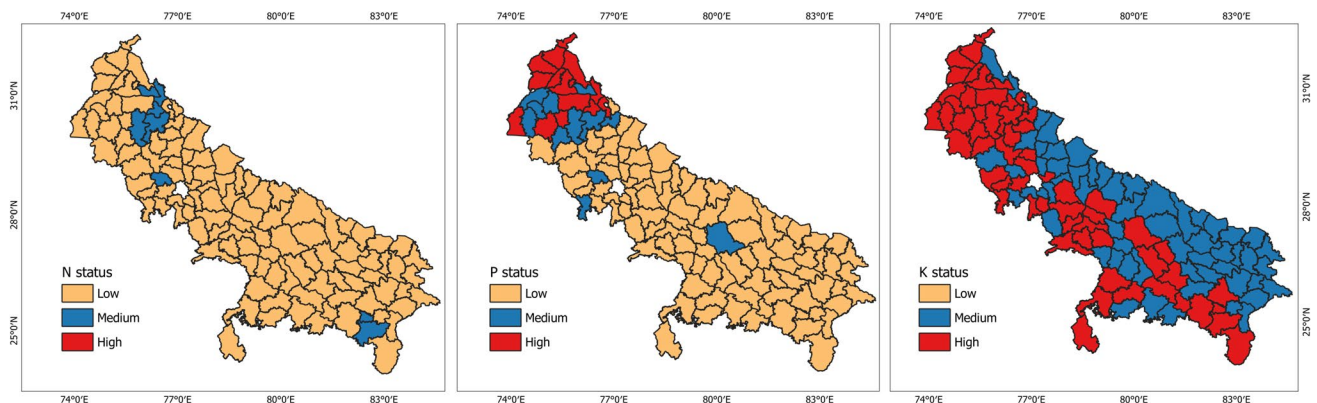


Fig. 5 District-level soil fertility status of NWIGP districts (N=nitrogen, P=phosphorus, and K=potassium). Source: Compendium on Soil Health (GOI 2012)

Table 1 High chemical pesticide consumption states in India. Source: Government of India (GOI; <https://ppqs.gov.in/statistical-database>)

S. no	State	Pesticide consumption in metric tonnes (2022–2023)	Rank (% share) in India	Pesticide consumption (Kg ha ⁻¹)
1	Uttar Pradesh	11,828	1 (21.4%)	51
2	Maharashtra	8718	2 (15.7%)	46
3	Punjab	5270	3 (9.5%)	68
4	Haryana	4068	4 (7.4%)	64

Methodology and data

Study area

The North Western Indo-Gangetic Plain (NWIGP) was selected as the study area which includes three states namely, Punjab, Haryana, and Uttar Pradesh (Fig. 1a). The study area has 337,860 km² geographical area and lies between 24°29′–32°28′ N latitude and 74°35′–84°37′ E longitude. The terrain is flat to a gently undulating plain with elevation ranging from 300 m above the mean sea level (MSL) in the north to 286 m in the south and 176 m in the south-west to 63 m in south-east. The climate varies from semi-arid to arid subtropical climate. The main source of rainfall is the southwest monsoon and the annual average rainfall varies from 350 to 1160 mm. The RW cropping system is grown in the three NWIGP states except western UP where sugarcane is a dominant crop. Major rivers (Ganga, Yamuna, Sutlej, Ravi, and Beas) flowing out of the Himalayas provide water for major irrigation systems. Irrigation water relies on groundwater resources in the NWIGP due to protective canal irrigation schemes. The major problems in the region are groundwater decline along with poor irrigation efficiency, excessive use of fertilizers and pesticides, and soil health degradation.

Data

Data sources

This study used data from district to national levels, sourced from different national and international organizations. The district-level area, production, yield, irrigated area under crop, and fertilizer consumption data are obtained from the Statistical Abstract of Punjab, Haryana, and Uttar Pradesh, District-wise Crop Production Statistics provided by the Ministry of Agriculture, Government of India (GOI; <https://aps.dac.gov.in/LUS/Public/Reports.aspx>), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT; <http://data.icrisat.org/dld/src/inputs.html>). GW extraction, recharge, and level data are provided by CGWB, Ministry of Jal Sakti, GOI (<https://indiawris.gov.in/wris/#/groundWater>). A

comprehensive status of essential nutrients in the soil can be obtained by examining the district soil fertility information of India released by the Indian Institute of Soil Science, Bhopal. Rainfall data is obtained from the Indian Meteorological Department (IMD).

Groundwater irrigation extraction

Groundwater irrigation extraction (ext, in ha-m) was estimated according to Eq. (1).

$$GW_{\text{ext}} = WC_{\text{irr}} \times GW_{\text{frac}} \quad (1)$$

Here, WC_{irr} is the total irrigation water consumption (in ha-m), and GW_{frac} is the groundwater use fraction.

The district-wise seasonal water consumption through irrigation (WC_{irr}) was computed for rice in the Kharif (June–October) and for wheat in the Rabi (November–May) season (Eq. (2)). All the areas under crop have been assumed as irrigated areas.

$$WC_{\text{irr}} = c_{i,\text{irr}} \times d_i \quad (2)$$

Here, $c_{i,\text{irr}}$ denotes an irrigated area (ha) for crop i , and d_i denotes the seasonal water consumption for flood or drip irrigation or sprinkler or CA in millimeters (mm), mentioned in Table 2. For, CA, a reduction of 40% in water use is assumed based on a literature review (Singh et al. 2016; Jat et al. 2020; Biswakarma et al. 2021; Rana et al. 2022; Gora et al. 2022; Fagodiya et al. 2023).

GW_{frac} was estimated using district-level data (source: Crop Production Statistics, GOI) according to Eq. (3).

Table 2 Seasonal irrigation water consumption. Values are modified based on Fishman et al. (2015), Singh et al. (2016), Bhardwaj et al. (2018), Surendran et al. (2021), and Brar et al. (2022)

Crop	Irrigation water use (mm)			
	Flood	Drip	Sprinkler	LLL
Rice (Kharif)	1200	600	850	950
Rice (Rabi/summer)	1600	800	1150	1250
Wheat	450	275	320	350

$$GW_{\text{frac}} = \frac{\text{Area}_{\text{irr, GW}}}{\text{Area}_{\text{irr, GW}} + \text{Area}_{\text{irr, SW}}} \quad (3)$$

Here, $\text{Area}_{\text{irr, SW}}$ is the area irrigated by surface water (SW) sources (in ha), and $\text{Area}_{\text{irr, GW}}$ is the area irrigated by groundwater (in ha).

Systemic literature review

This study conducted a systematic literature review (SLR) to structure and critically evaluate the existing irrigation, nutrient, and pesticide management research in the NWIGP. The SLR was conducted using the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) method (Liberati et al. 2009). Three main steps of the PRISMA method, search strategy for literature, selection and eligibility criteria, extracting data, and summarizing, are explained in Supplementary Information. A total of 187 articles were obtained, including peer-reviewed publications and grey literature, with 94 from Web of Science and 93 from Scopus (Table S1). The first screening stage involved eliminating any duplicated publications, leaving 111 articles for further evaluation (Fig. S1). Of these, 38 were excluded for not meeting the set quality criteria, leaving 73 articles for analysis (Table S2, S3). The data obtained through in-depth reading of the final set of articles were recorded in an MS Excel spreadsheet. The selected studies were categorized into different thematic groups based on their research focus, geographical location, irrigation, nutrient, pesticide management, groundwater, soil health, research findings, and identified problems. Policy recommendations and relevant stakeholder information were also extracted from the literature whenever available. Lastly, all the collected information is correlated with the relevant sections and subsections within this paper.

Impact on groundwater resource

Irrigation management

Conventional rice cultivation is water-intensive to maintain ponding depth for more than one month after intense tillage, resulting in significant water losses through puddling, evaporation, and percolation (Rana et al. 2022; Shah et al. 2023). Despite its inefficiency, surface flood irrigation (FI) remains the dominant method, resulting in low water use efficiency (WUE) and the leaching of nutrients and pesticides into water bodies (Verma et al. 2023). GW serves as the primary irrigation source due to subsidized electricity and limited canal water access, with conventional FI resulting in more than 55% water wastage, exacerbating unsustainable GW over-extraction (Brar et al. 2022). However, reducing water

usage may jeopardize crop yields, posing a significant challenge to food security. Therefore, to maintain agricultural productivity while alleviating stress on GW resources, substantial improvements in WUE are needed (Fishman et al. 2015). In response, many water-efficient techniques have emerged, including drip irrigation, sprinkler systems, and laser land leveling (Kahlowan et al. 2007; Jat et al. 2009; Surendran et al. 2021). If FI is entirely employed in the RW system, water consumption would reach 1.895, 4.085, and 9.575 Mha-m in Haryana, Punjab, and UP, respectively (Fig. 6a). The subsequent paragraphs detail the water-saving potential in each district through the transition from FI to water-saving techniques.

Laser land leveling (LLL) reduces the uneven distribution of irrigation water, thereby enhancing irrigation efficiency by ensuring precise water control and mitigating nutrient loss through improved runoff management (Jat et al. 2009). A study by Rickman (2002) reported a remarkable 24% increase in rice yields in laser-leveled fields compared to traditionally leveled (TLL) ones in IGP. Similarly, Jat et al. (2009) claimed a consistent 7% productivity increase in the RW system under LLL relative to TLL, with water savings of 10–12% in rice and 10–13% in wheat. District-wise water-saving analysis from FI to LLL conversion unveiled significant groundwater preservation, with Haryana, Punjab, and UP saving 0.405, 0.867, and 2.046 Mha-m, respectively (Fig. 6c). These findings align with Aryal et al. (2015), suggesting that even a 50% adoption of LLL in Haryana and Punjab's RW systems could save 0.270 Mha-m water with an additional 699 M kg of rice and 987 M kg of wheat, equating to USD 385 M annually in 2011.

Sprinkler systems, exemplified by portable rain guns, offer precise water application during pre-sowing and subsequent irrigations, introducing wet-dry cycles to rice fields instead of continuous saturation under conventional methods. This method has substantially enhanced on-farm irrigation efficiencies, reaching up to 80% in the Indian subcontinent's climatic conditions (Kahlowan et al. 2007). Notably, Kahlowan et al. (2007) claimed a 35% reduction in water consumption compared to FI while an 18% increase in rice yields in the IGP of Pakistan. In India, Kumar et al. (2018) observed a water savings of approximately 20% with sprinkler irrigation compared to FI. Our analysis reveals substantial GW conservation from flood to sprinkler conversion, with Haryana, Punjab, and UP saving 0.551, 1.188, and 2.782 Mha-m, respectively, compared to FI (Fig. 6b).

Drip irrigation (DI) is an efficient strategy to enhance WUE by mitigating surface runoff and evaporation (Sidhu et al. 2019). Sharda et al. (2017) reported 40% water savings with yield improvements upon transitioning from FI to DI in Punjab. Across the IGP, water savings ranging from 25 to 80% with the adoption of DI have been reported (Joseph et al. 2022). Furthermore, sub-surface drip irrigation

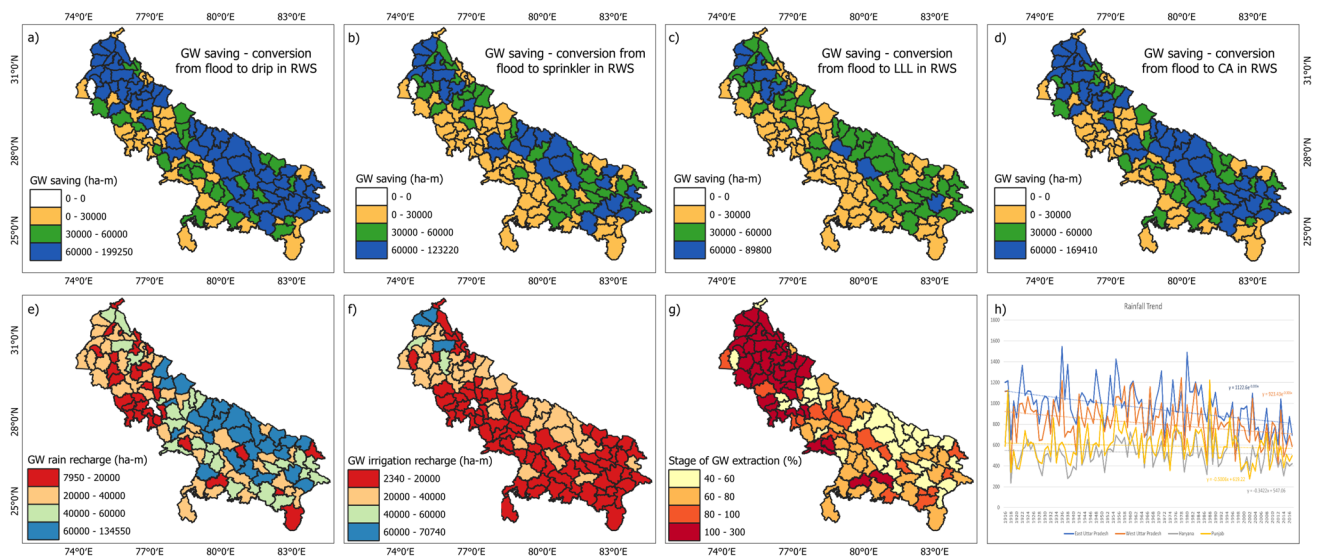


Fig. 6 Saving in groundwater due to implementation of water saving technologies **(a)** groundwater (GW) saving if conversion from flood to drip. **b** GW saving if conversion from flood to sprinkler. **c** GW saving if conversion from flood to LLL. **d** GW saving if conversion from

flood to CA. **e** GW recharge due to rain in 2020. **f** GW recharge due to irrigation in 2020. **g** Stage of GW extraction. **h** Trend of 100 years annual rainfall in Punjab, Haryana, Western and Eastern Uttar Pradesh (1916–2016)

(SSDI) in rice-based systems can save up to 61% more water over FI (Soman et al. 2018; Sandhu et al. 2019). Similarly, Fagodiya et al. (2023) reported 65, 40, and 60% savings of irrigation water in rice, wheat, and RW system, respectively, compared to FI. Transitioning from FI to DI, a widely advocated water-saving measure can yield substantial GW savings of 0.869, 1.913, and 4.380 Mha-m in Haryana, Punjab, and UP, respectively (Fig. 6a). A similar finding has been mentioned by Shah (2009) that DI reduces GW quantity pumped per hectare by 30–70%. Higher water savings in SSDI systems can be attributed to the targeted application of water based on crop needs, and reduced evaporation and deep drainage losses (Sidhu et al. 2019). In addition to its lower water requirements, drip irrigation offers several other advantages over traditional FI, including improved yield by 10–20%, reduced weed growth by 43–95% (especially *Phalaris minor*), enhanced nitrogen-use efficiency by 20%, and reduced cultivation costs (excluding implementation costs) and energy savings, and thereby eventually has a favorable effect on farm income (Jat et al. 2021; Joseph et al. 2022).

CA practices significantly reduce water usage, with studies by Singh et al. (2016) claiming 40% saving of water using CA in the RW system. Biswakarma et al. (2021) reported 23–37% lower evaporation with CA and effective soil moisture conservation with ZT. Kakraliya et al. (2018) demonstrated in their field experiments that CA practices resulted in irrigation water savings of 14–29% in rice and 12–36% in wheat compared to farmer practices. Similar results were reported by Sharma et al. (2018) and Jat et al.

(2020), with a 19–30% saving of irrigation water in rice. Our estimates reveal GW savings of 0.758, 1.634, and 3.830 Mha-m in Haryana, Punjab, and UP, respectively (Fig. 6d). The adoption of CA alone resulted in a water savings of 27.3% compared to CT, while the combination of CA and SSDI practices led to even greater water savings of 50.8% (Rana et al. 2022). Therefore, SSDI, coupled with CA, offers a promising fusion of technologies for water saving. Implementing these practices on a larger scale has the potential to alleviate pressure on GW resources, improve crop yields, and contribute to the long-term sustainability of agricultural systems.

Groundwater recharge and level

Between 2008 and 2016, Punjab and Haryana received a notable increase in annual precipitation (50 to 80 mm) compared to the preceding period of 2002 to 2007 (30 to 50 mm) (Fig. 6h). Despite this rise in rainfall, the annual GW level experienced a significant decline from 2010 to 2017, suggesting an alarming trend of excessive GW extraction for irrigation purposes. In the western region, low permeability layers beneath paddy fields inhibit rainwater recharge, leading to minimal recharge from precipitation (Fig. 6e). Instead, a substantial portion (60–70%) of GW recharge in Punjab and Haryana originates from sources other than rainfall, including seepage from canals, tanks, ponds, and irrigation return flows (CGWB 2019). FI, a commonly used method, is expected to facilitate groundwater recharge; however, the widespread practice of conventional

rice cultivation hinders water infiltration to deeper soil levels, limiting recharge capacity (Joseph et al. 2022). In the context of CA, as noted by Thierfelder and wall (2009), the formation of stable aggregates accelerates the infiltration rates approximately by 50% compared to conventionally tilled areas on sandy loam soils, which are prevalent in the NWIGP region. A simulation by Chakraborti et al. (2023) observed a 34% increased net GW recharge (subtracting the extraction from the recharge) by transitioning from FI to DI in Uttar Pradesh. Moreover, as farmers transition from FI to DI, they often construct affordable unlined reservoirs to maintain water availability during periods of scarcity that can facilitate a substantial recharge of 7.5% of the annual rainfall, depending on the soil characteristics of the region (Sharda et al. 2006).

Adoption of drip irrigation can substantially reduce the decline in GW levels. Model analysis by Sishodia et al. (2018) suggested that the use of DI can mitigate GW decline during rainfall deficit years. A similar finding has been reported by Joseph et al. (2022), indicating the reduction in GW depletion in Punjab and Haryana. However, irrespective of the geographical area, changes in the frequency of water application do not elicit a significant response in GW levels (Joseph et al. 2022). This observation aligns with the findings of Fishman et al. (2015), who noted that while enhanced efficiency of irrigation practices can partially mitigate unsustainable extraction of GW in the NWIGP, it cannot alter the overall trend of groundwater level decline. Therefore, solely improving irrigation efficiency may not alleviate stress on GW resources in regions, as it leads to a reduction in irrigation return flow (Dangar et al. 2021). Consequently, prioritizing the enhancement of GW recharge through the implementation of artificial GW recharge structures and watershed development initiatives becomes imperative for long-term sustainability.

Crop switching

In NWIGP, particularly in Haryana and Punjab, key contributors to India's food grain supply, achieving maximum theoretical efficiency may slow down the rate of GW table decline but cannot reverse it (Fishman et al. 2015). Moreover, the adoption of efficient irrigation techniques does not always guarantee of reduction in GW decline rate, as it may reduce return flow (Chakraborti et al. 2023). Therefore, sustainable water management in such regions will necessitate complementary approaches, such as switching cropping patterns toward less water-intensive crops (Fishman et al. 2015). Given that rice is not water-efficient, a switch in dietary preferences from rice to alternatives like maize or millet could reduce irrigation water demand by up to 33% (Davis et al. 2018). Transitioning to less water-demanding crops, such as pulses, from rice, can reduce GW depletion rates.

With enabling price policies and providing marketing facilities, pulses such as pigeon peas, which are highly favored in the NWIGP, can be promising crops. However, it needs to be planted in well-drained or upland fields to avoid water logging. Results from the crop switching model indicated 55% and 9% water savings in the Kharif and Rabi seasons, respectively, compared with current practices by replacing rice with millet and sorghum in Kharif and wheat with sorghum in Rabi (Chakraborti et al. 2023). The combination of transitioning from flood to drip irrigation and switching crops can lead to a substantial improvement, with a 78% reduction in GW depletion across the IGP (Chakraborti et al. 2023). Therefore, the integration of water-saving technologies with crop diversification (part of CA) emerges as a promising solution to sustain GW use.

Impacts of chemical fertilizers and pesticides

The indispensable role of fertilizers and pesticides in agriculture is undeniable, yet with increasing awareness of their impacts, it is crucial to assess their impact on soil and water, emphasizing the need for sustainable farming practices. Therefore, this section critically examines current practices in nutrient and pesticide management and their potential implications on soil health and groundwater resources.

Current status of fertilizer and pesticide management

Rice and wheat account for about 53% of India's total fertilizer nitrogen usage (FAO 2022). In 2000, surveys revealed that farmers applied higher than recommended N doses (130 to 195 kg ha^{-1}), less P (11 – 14 kg ha^{-1}), and limited K to rice and wheat in the NWIGP (Yadav et al. 2000). Singh et al. (2013) and Kakraliya et al. (2018) confirmed these findings within the IGP. Farmers frequently apply more N than recommended due to improper application practices with many farmers using it indiscriminately in an attempt to boost yields (Fagodiya et al. 2023). However, the application of P, K, secondary nutrients, and micronutrients remains significantly limited (Shivay et al. 2019). Additionally, the practice of residue burning exacerbates soil nutrient depletion and causes multiple nutrient deficiencies, impacting crop productivity (Bhatt et al. 2016; Biswakarma et al. 2022).

Recommended NPK fertilizer doses vary among studies in the NWIGP, as detailed in Table 3. The usually followed fertilizer practice in scientific experimental fields is to apply the total recommended doses of P and K, and half or two-thirds of the total N through urea ($46\% \text{ N}$), single superphosphate ($46\% \text{ P}_2\text{O}_5$), and muriate of potash ($60\% \text{ K}_2\text{O}$) before sowing. The remaining N is applied in two splits during tillering and panicle initiation stages or

Table 3 The recommended dose of fertilizer for rice and wheat in the NWIGP

Recommended dose	Crop	Study area	References
150:26:50 N:P:K kg ha ⁻¹	Rice	CSSRI, Haryana Karnal, Haryana	(Fagodiya et al. 2023; Jat et al. 2020) (Gora et al. 2022; Kakraliya et al. 2018)
150:26:33 N:P:K kg ha ⁻¹ + 25 kg ZnSO ₄ ha ⁻¹ + 7 kg FeSO ₄ ha ⁻¹	Rice	CSSRI, Haryana	(Singh et al. 2022b)
150:26:50 N:P:K kg ha ⁻¹ + 25 kg Zn ha ⁻¹	Rice	Karnal, Haryana CCSHAU, Haryana	Choudhary et al. (2018) Saharawat et al. (2010)
150:13:25 N:P:K kg ha ⁻¹	Rice	PAU, Punjab	Thind et al. (2023)
150:26:25 N:P:K kg ha ⁻¹	Rice	PAU, Punjab	Saikia et al. (2019)
150:26:33 N:P:K kg ha ⁻¹	Rice	IARI, New Delhi	Raj et al. (2022)
150:26:50 N:P:K kg ha ⁻¹	Wheat	Karnal and CCSHAU, Haryana	(Singh et al. 2022b; Saharawat et al. 2010; Gora et al. 2022; Jat et al. 2020, 2021; Kakraliya et al. 2018)
150:26:33 N:P:K kg ha ⁻¹	Wheat	IARI, New Delhi	Raj et al. (2022)
120:26:33 N:P:K kg ha ⁻¹	Wheat	IARI, New Delhi IIMR, New Delhi	Das et al. (2013) Parihar et al. (2017)
120:26:33 N:P:K kg ha ⁻¹	Wheat	IARI, New Delhi	(Biswakarma et al. 2021, 2022)
120:26:25 N:P:K kg ha ⁻¹	Wheat	PAU, Punjab	(Thind et al. 2017, 2023)
150:26:25 N:P:K kg ha ⁻¹	Wheat	PAU, Punjab	Saikia et al. (2019)

in three splits depending on crop sensitivity (Thind et al. 2017; Jat et al. 2020). Farmers in the IGP frequently apply excessive fertilizer doses rather than adhering to recommended levels (Singh and Singh 2012). This reluctance may be due to a lack of instructions or information, the high costs of recommended fertilizer mixes, and poor access to technical guidance (Fishman et al. 2016). It is important to note that specific fertilizer guidelines for CA have not been fully established. In spite of the fact that CA shows a better nutrient response and may necessitate lower amounts of fertilizers compared to conventional methods when CA-specific recommendations are followed. Numerous multi-location trials, summarized in Table 4, indicate that CA not only enhances nutrient efficiency compared to conventional practices but also reduces fertilizer requirements thereby reducing the cost of cultivation.

Herbicide resistance poses a significant challenge in the IGP (Yadav et al. 2016). Under the monocropping culture of RW, *Phalaris minor* (*P. minor*) infestation in wheat is increased, as it thrives under anaerobic conditions fostered during rice cultivation (Soni et al. 2023). To effectively manage *P. minor*, a tank mix solution containing total (sulfosulfuron + metsulfuron) at a rate of 16 g ha⁻¹ was applied 25–30 days after sowing (Chauhan and Opeña 2012). In certain locations in Haryana, farmers exceeded the recommended herbicide dosage by 3–4 times during the 2017–2018 season, resulting in inadequate weed control of approximately 65% (Singh et al. 2021). Additionally, *P. minor* is developing resistance to multiple commonly used herbicides. Reported cases of resistance include sulfosulfuron, isoproturon,

mesosulfuron-methyl, clodinafop-propargyl, pyroxsulam, fenoxaprop-*p*-ethyl, iodosulfuron-methylsodium, and pinoxaden (Jat et al. 2021; Soni et al. 2023).

The standard weed management practice usually involves two herbicide applications, one pre-emergence (PRE) and one post-emergence (POST), along with one round of manual weeding. Various researchers have proposed recommended practices, as summarized in Table 5. For example, Singh et al. (2022b) recommended using pendimethalin at a rate of (@) 0.75 kg active ingredient per hectare (a.i.ha⁻¹) as PRE within 2 days after sowing (DAS) followed by bispyribac-sodium @0.025 kg a.i.ha⁻¹ as POST at 25 DAS and one manual weeding for leftover weeds at 35 DAS for effective weed management in rice. Similarly, for wheat, a tank mix of pinoxaden @0.05 kg a.i.ha⁻¹ or clodinafop-ethyl and metsulfuron @60 and 4 g a.i.ha⁻¹, respectively, at 30 DAS ensures effective control (Jat et al. 2020; Gora et al. 2022). In CA practices, glyphosate @1.0 kg a.i.ha⁻¹ is commonly applied in ZT fields to control existing grassy, broad-leaved, and sedge weeds before sowing preceding crops like rice and wheat (Kakraliya et al. 2018), followed by the same practice as mentioned above. It is noteworthy that while most studies focus on herbicides,³ our emphasis in the following sections will be more on insecticide and fungicide use.

³ Based on the Scopus and Web of Science database searches using broad terms such as “Pesticide AND Gangetic Plain” (includes Indo-Gangetic Plain, Northwestern Gangetic Plain).

Table 4 Fertilizer reduction in conservation agriculture (CA) as compared to conventional practices (CT) and N P K availability in soil (0–15 cm) in the NW IGP

Cropping system	Study area	Fertilizer reduction in CA versus CT	Available N P K in soil (0–15 cm)	Description	References
Rice–wheat	CSSRI, Haryana	N: -79.4 kg ha^{-1} P: 0 kg ha^{-1} K: 0 kg ha^{-1}	N: $188.9 \pm 10.9 \text{ kg ha}^{-1}$ P: $32.7 \pm 6.1 \text{ kg ha}^{-1}$ K: $270.1 \pm 11.3 \text{ kg ha}^{-1}$ OC: 0.53%	System productivity under CA practices with drip irrigation in reduced-tilled direct seeded rice (RTDSR) and zero-tilled wheat (ZTW) with 100% rice residue (RR) is at par with conventional practice (PTR)	Fagodiya et al. (2023)
Rice–wheat–fallow	CSSRI, Haryana	N: -61 kg ha^{-1} P: $+2.5 \text{ kg ha}^{-1}$ K: $+60 \text{ kg ha}^{-1}$	N: $120.2 \pm 3.2 \text{ kg ha}^{-1}$ P: $5.7 \pm 0.2 \text{ kg ha}^{-1}$ K: $230.6 \pm 2.3 \text{ kg ha}^{-1}$ OC: 4.8 g kg^{-1}	System productivity under CA practices with conventional tillage (CT) DSR and ZTW with 100% RR + 25% wheat residue (WR) retention has 6.14% more yield and 11.71% more return compared to conventional practice	Gora et al. (2022)
Rice–wheat	Farmers' field in Karnal, Haryana	N: -116 kg ha^{-1} P: -15 kg ha^{-1} K: $+118 \text{ kg ha}^{-1}$	N: $173 \pm 7.2 \text{ kg ha}^{-1}$ P: $24.9 \pm 2.7 \text{ kg ha}^{-1}$ K: $308 \pm 41.3 \text{ kg ha}^{-1}$ OC: 0.59%	System productivity under CA practices with RTDSR + ZTW with 100% RR + 25% WR retention has 8.2% more yield and 18.6% reduction in the cost of cultivation compared to conventional practice	Kakraliya et al. (2018)
Rice–wheat	PAU, Punjab	No difference	N: NA P: 18.37 kg ha^{-1} K: $112.90 \text{ kg ha}^{-1}$ OC: 4.5 g kg^{-1}	System productivity under CTDSR + ZTW + RR was 5% higher than the conventional practice PTR + CTW – R, resulting in Rs 17,000 ha^{-1} greater net returns	Thind et al. (2023)
Rice–wheat	PAU, Punjab	N: -75 kg ha^{-1} P: 0 kg ha^{-1} K: 0 kg ha^{-1}	N: NA P: 25.31 kg ha^{-1} K: $103.71 \text{ kg ha}^{-1}$ OC: 3.51 g kg^{-1}	System yield in PTR with 25% WR + ZTW + RR was 17.06% higher than the conventional practice PTR + CTW – R	Saikia et al. (2019)

NA Not Available, -: Reduction in CA, +: Addition in CA, N Nitrogen, P Phosphorus, K Potassium, OC Organic Carbon, RTDSR Reduce-tilled Direct Seeded Rice, ZTW Zero-tilled Wheat, RR Rice Residue, WR Wheat Residue, CT Conventional Tillage, PTR Puddled Transplanted Rice

Impacts on soil health

Soil health is characterized by three main parameters: biological (soil microbial activities, microbial community, and respiration), chemical (pH, electrical conductivity, nutrient availability, and soil organic matter), and physical (texture, bulk density, and water holding capacity) (Larson and Pierce 1994). These parameters are interconnected and exert mutual influence. The prolonged and intensive application of chemical fertilizers and pesticides in the soil can have diverse effects on soil health (Prashar and Shah 2016; Baweja et al. 2020). Additionally, the burning of rice residue negatively

affects soil health (Jain et al. 2018). Therefore, this section presents the impact of fertilizers and pesticides on soil properties, soil microflora, and fertility.

Soil properties

Excessive fertilizer use poses various risks to soil health, including soil acidification, compaction, erosion, runoff, contamination, and a decline in soil organic matter (SOM) content (Rahman and Zhang 2018; Pahalvi et al. 2021). Additionally, intensive tillage in CT systems leads to a decrease in SOM due to the accelerated oxidation

Table 5 Pesticide management in rice and wheat in the NWIGP

Pesticide practice	Crop	Study area	References
Pretilachlor @ 1.0 kg ha ⁻¹ PRE at 3 DAT	Rice (PTR)	CSSRI, Haryana IARI, New Delhi	Singh et al. (2022b) Das et al. (2013)
Butachlor @ 1.25 kg ha ⁻¹ PRE at one DAT	Rice (PTR)	Karnal, Haryana	Kakraliya et al. (2018)
Pendimethalin @ 1.0 kg ha ⁻¹ or pretilachlor @ 1.25 kg ha ⁻¹ + hand weeding at 30–35 DAS	Rice (PTR)	Karnal, Haryana	Choudhary et al. (2018)
Anglophones @ 0.4 kg ha ⁻¹ + need-based hand weeding	Rice (PTR)	CCSHAU, Haryana	Saharawat et al. (2010)
Pendimethalin @ 0.75 kg ha ⁻¹ as PRE within 2 DAS + bispyribac-sodium @ 0.025 kg ha ⁻¹ POST at 25 DAS + one manual weeding at 35 DAS	Rice (DSR)	CSSRI, Haryana PAU, Punjab	Singh et al. (2022b) Thind et al. (2023)
Pendimethalin @ 1.0 kg ha ⁻¹ PRE at 1 DAS + bispyribac-sodium @ 0.025 kg ha ⁻¹ POST at 20–25 DAS	Rice (DSR)	CSSRI, Haryana	Jat et al. (2020) Choudhary et al. (2018)
Pendimethalin @ 1.0 kg ha ⁻¹ PRE within 2 DAS + bispyribac-sodium and pyrazosulfuron ethyl @ 10 g and 6 g ha ⁻¹ , respectively, at 20–25 DAS	Rice (DSR)	Karnal, Haryana	(Gora et al. 2022; Kakraliya et al. 2018)
Pyrazosulfuron ethyl @ 0.025 kg ha ⁻¹ as PRE + tank-mixture of cyhalofop-butyl @ 0.100 kg ha ⁻¹ and bispyribac-sodium @ 0.025 kg ha ⁻¹ at 25 DAS	Rice (DSR)	IARI, New Delhi	Raj et al. (2022)
Pendimethalin @ 1.0 kg ha ⁻¹ at 2 DAS + need-based hand weeding	Rice (DSR)	CCSHAU, Haryana	Saharawat et al. (2010)
Pendimethalin @ 1.5 kg a.i. ha ⁻¹ as PRE + pinoxaden @ 0.05 kg a.i. ha ⁻¹ as POST at 20–25 DAS	Wheat	CSSRI, Haryana	Singh et al. (2022b)
Pinoxaden @ 50 g ha ⁻¹ or clodinafop ethyl and metsulfuron @ 60 and 4 g ha ⁻¹ , respectively, at 30–35 DAS	Wheat	Karnal, Haryana	(Gora et al. 2022; Jat et al. 2020; Kakraliya et al. 2018)
Sulfosulfuron + metsulfuron @ 0.032 kg ha ⁻¹ or clodinafop-ethyl + metsulfuron @ 0.060 kg ha ⁻¹ at 35 DAS	Wheat	Karnal, Haryana	Choudhary et al. (2018)
Pendimethalin @ 1.0 kg ha ⁻¹ PRE and cladinofop @ 0.060 kg ha ⁻¹ POST at 28–32 DAS	Wheat	IIMR, New Delhi	(Parihar et al. 2017, 2020)
Isoproturon @ 1.25 kg ha ⁻¹ + 2,4-D sodium salt @ 0.625 kg ha ⁻¹ at 35 DAS	Wheat	IIFSR, Uttar Pradesh	Jat et al. (2013)
Sulfosulfuron @ 0.35 kg ha ⁻¹ at 21 DAS + 2, 4D @ 0.5 kg ha ⁻¹ at 35 DAS	Wheat	CCSHAU, Haryana	Saharawat et al. (2010)

and breakdown of OM (Das et al. 2013). A study by Guo et al. (2010) reported severe soil acidification and reduced productivity resulting from the excessive application of synthetic fertilizer. Soil acidification, caused by the release of acidic compounds during nutrient transformations, accelerates the breakdown of mineral-rich soil aggregates essential for drainage, leading to soil compaction (Baweja et al. 2020). Soil compaction poses numerous challenges including inadequate aeration, increased bulk density, reduced permeability, erosion, and runoff (Mari et al. 2008; Batey 2009). Singh et al. (2014) reported increased bulk density under conventional RW systems due to the development of plow sole layers beneath the tilled soil surface, whereas CA showed reduced density, mitigating subsoil compaction. Moreover, repeated burning in RW reduces mineralizable N and C in the 0–15 cm soil layer, thereby negatively affecting OM mineralization and nutrient cycling (Jain et al. 2018). Conversely, residue retention enhances soil's chemical (organic carbon, nutrient cycling, pH), physical (structure, infiltration, erosion, compaction, soil moisture retention), and biological

(carbon sequestration, microbial activity, and diversity) quality (Singh et al. 2014; Saikia et al. 2019).

Soil organic carbon (SOC), a vital indicator of soil health, profoundly influences the physical, chemical, and biological properties of soil. Inorganic N fertilizer application can impact the decomposition and mineralization of OM due to altered microbial activity and balancing the C-to-N ratio. Moreover, pesticide retention correlates directly with SOM content. A study by Sapkota et al. (2017) found that the continuous cultivation of RW over seven years in the IGP led to a decline in SOC of 0.9 t ha⁻¹. Conversely, adopting CA practices yielded positive effects on soil health (Fig. 7). Studies by Das et al. (2013) and Biswakarma et al. (2022) reported a 15–24% higher total SOC stock under CA compared to CT in the RW system, mainly due to less disruption of soil structure and aggregates and increased carbon input from residue retention. Singh et al. (2014) recorded significant increases in SOC under ZT over 15 years: 19.04% in sandy loam, 34.73% in loam, and 38.77% in clay loam soils, compared to CT. This improvement is attributed to deeper wheat root penetration and reduced oxidation of in situ OM.

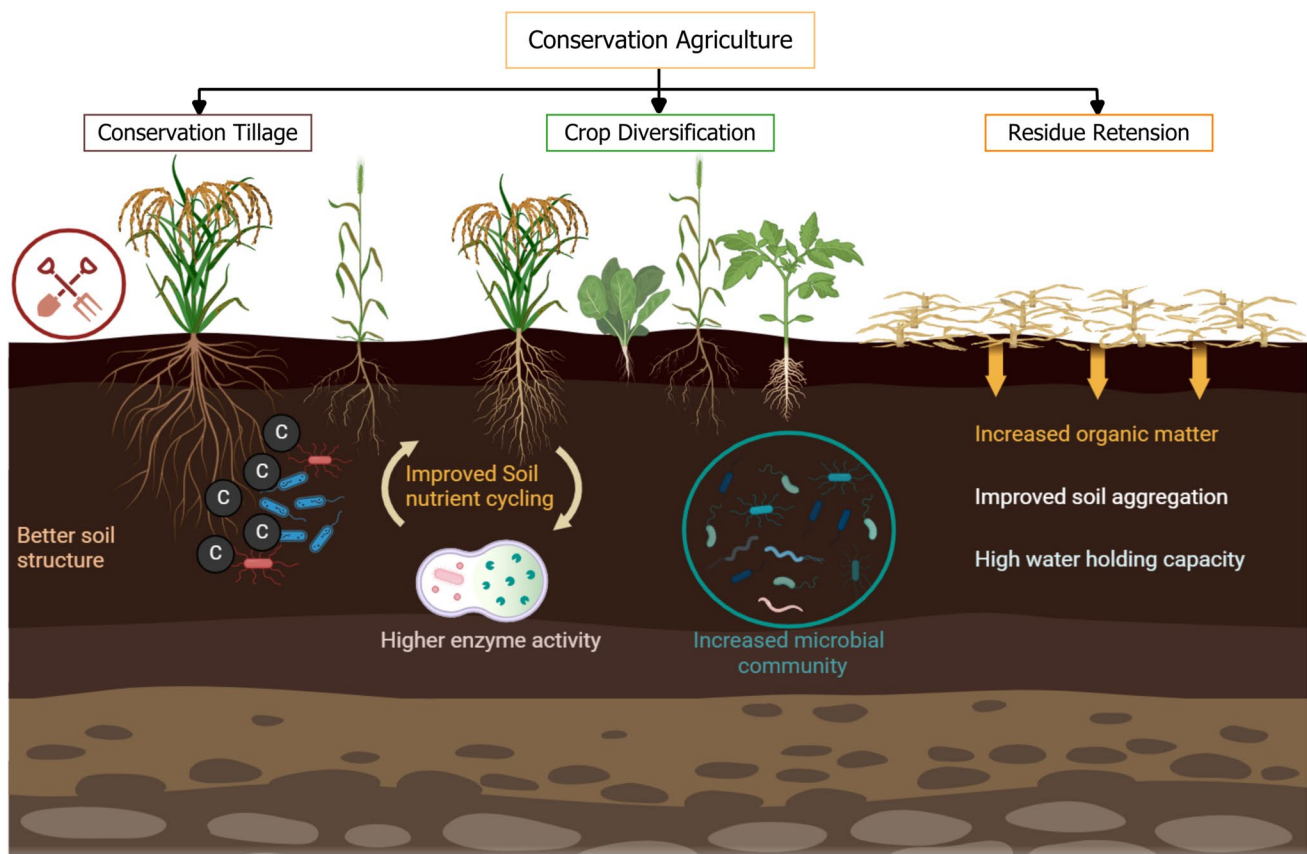


Fig. 7 Effect of conservation agriculture on soil health (created with biorender.com)

The higher OC content in clay loam soil can be attributed to its greater clay content, as clay content is directly proportional to OC levels. Moreover, the inclusion of mungbean in RW increased SOC by 83% over the RW system due to higher quantities of crop residues (Choudhary et al. 2018). Higher SOC content is associated with increased crop yields, even under extreme climatic conditions, emphasizing its importance for soil health, land degradation neutrality, and agricultural productivity in the context of climate change (NAAS 2021).

Soil microflora and fertility

The activities of various soil enzymes, such as alkaline phosphatases, dehydrogenase, proteases, ureases, and β -glucosidases, are crucial indicators of microbial community and soil fertility and understanding the impact of agricultural practices (Parihar et al. 2020). However, pesticides adversely affect enzyme activities like dehydrogenases and phosphatases, posing threats to soil health (Hossain et al. 2022). Mandal et al. (2019) provide a comprehensive overview of agrochemicals' impact on enzymes and microbial communities. Barreiro et al. (2016) observed a decline in β -glucosidase activity due to burning practices, a common practice in

the NWIGP. The heat generated by burning residues temporarily eradicates bacterial and fungal populations; nonetheless, recurrent burning can lead to a permanent decline in microbial populations (Jain et al. 2018). Conversely, Naresh et al. (2018) found that ZT and residue retention increased the number of nitrifying bacteria by up to 73% compared to CT. Similarly, Zhang et al. (2016) noted increased enzyme activities, such as urease and sucrase with straw application. Additionally, under CA, enzymatic activities including dehydrogenase, fluorescein diacetate, and β -glucosidase were 20–27% higher compared with CT, emphasizing the role of CA in enhancing soil enzyme activities (Parihar et al. 2020). Saikia et al. (2019) observed significant increases of 70.3 and 30.4% in dehydrogenase, and fluorescein diacetate activities, respectively, under CA with green manure compared to CT in RW system, resulting from ZT and rice straw addition. These findings emphasize the importance of CA, yet further research is needed to determine which CA practices effectively stimulate soil microbial communities in RW systems for long-term sustainability (Fig. 7).

The excessive application of inorganic fertilizers and pesticides has been found to reduce the population of beneficial soil microorganisms, such as *Pseudomonas aeruginosa*, indicating an adverse impact on soil health (Islam

et al. 2009; Prashar and Shah 2016). Furthermore, synthetic chemicals inhibit nitrogen-fixing rhizobia bacteria, leading to disruptions in nutrient cycling processes and ultimately increasing dependency on synthetic fertilizers (Rahman and Zhang 2018). Additionally, pesticide applications have led to a shift of plant-parasitic nematodes while reducing beneficial bacteria and fungi-feeding nematodes, vital for OM decomposition and biological control (Yardirn and Edwards 1998). Earthworms, bioindicators of chemical contamination, essential for maintaining healthy soil structure and fertility, have experienced decreased reproductive success, juvenile survival, and overall development due to pesticides like glyphosate and parathion (Yasmin and D'Souza 2010). However, a study by Mishra et al. (2021) showed that the earthworm population doubled under CA compared to CT. Glyphosate, an extensively used herbicide, reduces populations of mycorrhizal fungi and viable spores for beneficial arbuscular mycorrhizal fungi (AMF) by up to 56%, subsequently affecting root development by up to 40% (Druille et al. 2016; Newman et al. 2016). Similarly, applications of common fungicides like captan have been associated with declines in populations of nitrogen-fixing bacteria and archaea, while favoring denitrifiers (Martinez-Toledo et al. 1998). Additionally, fungicide applications are also linked to decreases in both the number and type of soil fungi, especially AMF, essential for the formation of macroaggregates crucial for soil structure (Kalia and Gosa 2011). Insecticide use further destabilizes the soil microbial community, altering beneficial species ratios and ecosystem functions, and leading to increased sensitivity to disturbance (Wu et al. 2021). The prolonged presence of pesticides in soil exacerbates shifts in microbial populations, underscoring the importance of rigorous testing of newly arriving commercial pesticide products before widespread usage by farming communities to mitigate adverse environmental impacts.

Impacts on groundwater resources

Inorganic fertilizers, highly water-soluble, leach into groundwater with irrigation, contributing to severe contamination in the NWIGP (Verma et al. 2023). The region has become a major hotspot for groundwater nitrate pollution due to extensive nitrogenous fertilizer application, with alarming concentrations (700–2000 mg/L) recorded in Punjab and Haryana (Kumari and Rai 2020; Pant et al. 2020). Notably, in Punjab, 92% of sites exceeded safe nitrate limits set by the Bureau of Indian Standards (45 mg/L), posing significant health risks to the local population (Ahada and Suthar 2018). Moreover, high nitrate levels in groundwater impact soil nitrogen fluxes when used for irrigation, further exacerbating contamination issues (Stuart et al. 2011). The Central Pollution Control Board (CPCB) has detected pesticides like Alachlor, Atrazine, Lindane, and Chlorpyrifos in

groundwater, with Haryana and Punjab identified as the most vulnerable states to pesticide pollution (Dutta et al. 2018). Studies have revealed concerning concentrations of endosulfan and DDT in groundwater samples from districts like Ambala and Gurgaon in Haryana, as well as the presence of various pesticides (endosulfan, DDT, Aldrin, Dieldrin, Heptachlor) in UP (Singh et al. 2005; Kaushik et al. 2012). To mitigate nitrate and pesticide contamination, measures akin to the Nitrate Directive implemented by the European Union (EU) are essential, emphasizing reduction at the source through legislative laws and promoting good farming practices (EU 1991). The EU's fertilizer reduction initiatives have shown promising results (250 to 160 kg/ha), underlining the importance of similar regulations and continuous evaluation to combat groundwater pollution, especially in severely affected regions like the NWIGP.

Challenges and opportunities

Soil health

The Committee on Doubling Farmers' Income reported that approximately 120 Mha of arable land in India suffers from different forms of land degradation, with 29.4 Mha exhibiting reduced fertility due to chemical contamination (GOI 2018). CA practice may be a feasible solution to degraded land as it has been proven to avert soil health degradation and improve soil properties. Furthermore, the Government of India introduced the Soil Health Card Scheme in 2015, which aims to provide farmers with scientific recommendations based on 12 village-level soil nutrients (both macro and micro) to guide their fertilizer and manure applications. Yet, there has been no comprehensive assessment of the scheme's effectiveness in mitigating pollution.

Crop residue retention is considered a sustainable method for improving soil health. In Northwestern India, paddy straw is typically not used as livestock feed due to its high silica content and limited technical or economically viable disposal options, leading farmers to burn rice residue for timely wheat sowing. Crop residue burning has numerous negative impacts on various environmental matrices. However, in Punjab and Haryana, where irrigated agriculture is prevalent, rice straw can be retained for better soil health and other associated benefits as sufficient soil moisture helps in its decomposition. In areas with limited water availability or rainfed agriculture, combining crop residue retention with less persistent chemicals (such as partial nitrogen fertilizer, straw ripening agents, and lime) can enhance residue decomposition by stimulating soil microbial activity.

The effectiveness of CA in increasing yields depends on the use of herbicides. However, the negative effects of herbicides on the environment and human health pose a threat

to the sustainability of CA practices. We posit that DSR may lead to higher levels of chemical residues, although there is a lack of substantial research on residue contamination and ways to mitigate it. Nonetheless, it is argued that crop diversification based on CA principles has the potential to reduce the reliance on chemicals, especially with the use of crop residue mulch for weed control. Additionally, progress can be made by developing aerobic rice varieties that are suitable for DSR.

Soil contamination by pesticide residues is a major issue due to the persistent nature of pesticides and their potential toxicity to humans. The long persistence of pesticides beyond their application season poses potential risks in terms of environmental impacts and harm to sensitive rotational crops. For example, residues of imazethapyr pose a damaging risk to wheat (Raj et al. 2022). The off-site transportation of contaminants through water and wind erosion further compounds the problem, affecting non-target species. Therefore, systematic monitoring of pesticide levels in soil is critical for promoting soil health and sustainable agricultural practices. A recent study in 11 EU countries revealed that approximately 83% of tested topsoil samples contained 76 different pesticide residues (Vera et al. 2019). However, such studies in India are scarce, highlighting the need to assess pesticide residues and their potential risks to the environment and ecosystem services.

Groundwater management

In Punjab and Haryana, about 92–96% of groundwater withdrawal is used for irrigation purposes. However, the extensive dependence on groundwater and insufficient availability of alternative infrastructure in the NWIGP has led to a steady decline in groundwater levels. Alarming estimates from the CGWB indicate that approximately 80% of the 138 monitored blocks in Punjab are overexploited (CGWB 2019). Similarly, in Haryana, around 61% of blocks are overexploited, with only 20% classified as safe (Fig. 6g). The decline in groundwater resources also reduces the baseflow of major Indian rivers by about 0.30 ± 0.07 cm/year or 2.39 ± 0.56 km³/year (Mukherjee et al. 2018). Furthermore, the provision of free electricity for agriculture further exacerbates this situation. The increasing depth of the groundwater table in NWIGP has several negative consequences. Firstly, it raises pumping costs since traditional centrifugal pumps become inadequate, requiring the use of more expensive submersible pumps to access deeper groundwater. Secondly, the expansion and maintenance of tube well infrastructure incur additional expenses. Lastly, the declining groundwater quality becomes a concern, as the upward movement of salts from deeper layers and the intrusion of saline water into fresh groundwater potentially render it unusable.

Groundwater irrigation through electric tube wells is dominant, with 72% of the total tubewell number (GOI 2018). The agricultural sector's electricity consumption in India has increased 54 times from 1969 to 2016, highlighting the heavy reliance on electricity for irrigation (Singh et al. 2022b). This situation is influenced by farmers' preference for pumping irrigation water from tube wells rather than relying on canal water, which often suffers from unreliable supply, poor maintenance, and inefficiency. The irrigation infrastructure utilizing groundwater plays a significant role in India's economy, contributing over 10% to the country's gross domestic product (GDP) and meeting 60% of its irrigation requirements (Scott and Sharma 2009). Despite significant utilization, only 58% of the identified groundwater resources have been developed thus far, indicating untapped potential for further development (Singh et al. 2022b). Additionally, the implementation of incentives, metered tariff policies for groundwater conservation, and regulated monitoring of groundwater levels and electricity usage for pumping are recommended.

The estimates indicate the possibility of enhancing WUE by up to 60%, from the existing level of 35–40% which can be achieved by modernizing distribution channels, implementing institutional innovations like participatory irrigation management (PIM), and adopting water-efficient technologies such as micro-irrigation (MI, drip/sprinkler system). The area covered by drip irrigation in states within the IGP ranges from 0.1 to 2.5% of its total potential. The limited adoption of MI in the NWIGP region can be primarily attributed to (a) high capital costs; (b) poor administration: Inefficient subsidy disbursement by state administrations; (c) subsidized or free electricity: deter farmers from investing in water-saving technologies; (d) limited promotion and awareness of implementation and benefits; (e) lack of technical expertise and IT support service; (f) stagnation in micro-irrigation expansion post-National Mission on Micro Irrigation (NMMI-2010–14) merger with National Mission for Sustainable Agriculture (NMSA); and (g) fragmented farmers' field. To better serve small and marginal farmers, there is a critical need to redesign low-cost drip and MI systems. One potential solution to tackle the fragmented field problem could involve the government developing a gravity-fed drip system and centralized reservoir for drip irrigation systems. Lastly, the formation of dedicated government/cooperative bodies, such as the Andhra Pradesh Micro Irrigation Project (with a 26% adoption rate), can help increase the adoption rate of MI.

It is essential to recognize that technology adoption and demand-side management alone may not suffice to stabilize water tables, necessitating the consideration of supply-side management strategies, such as artificial recharge. Therefore, comprehensive policy interventions are needed, encompassing water pricing, infrastructure development, awareness

programs, restoration of canal water supply, increased aquifer recharge, and the promotion of sustainable water management practices to ensure the long-term sustainability of groundwater in the region.

Sustainable intensification and diversification

Sustainable intensification coupled with diversification based on CA practices is crucial to ensure food security, improve resource use efficiency, and minimize negative environmental impacts. For instance, using maize instead of rice requires 80–85% less water and exhibits 8–22 times higher water productivity (Kumar 2018; Jat et al. 2020). Additionally, incorporating mungbean in maize-wheat (MW) systems increased system productivity by 38% and total water productivity by 270% compared to PTR (Choudhary et al. 2018). CA-based multiple cropping systems like summer mungbean-maize-wheat and maize-chickpea-sesbania, supported by SSDI, can increase maize grain yield by 35–38.7% over conventional practices (Yadav et al. 2015b; Brar et al. 2022). Sustainable intensification and diversification of cereal systems not only enhance crop, water, and nutrition productivity but also improve soil and environmental health (Banjara et al. 2021). Incorporating mungbean in cereal systems positively impacts soil properties through higher carbon addition and increased C- and N-cycle enzyme activities (Jat et al. 2020; Das et al. 2021). Studies also show increased NPK nutrient uptake when legumes are incorporated into cereal systems, enhancing cropping system sustainability (Yadav et al. 2015b). Furthermore, rotating leguminous crops in rice-wheat systems effectively suppress annual weeds like *P. minor* and *A. arvensis* (Shahzad et al. 2016; Jat et al. 2021). We acknowledge that these results should be interpreted with caution due to higher-level processes and complex interactions beyond the field level.

Despite the several advantages of intensifying and diversifying the CA-based MW system, certain concerns discourage the adoption of maize as a diversification option for rice. Such concerns are crop sensitivity to waterlogging during the monsoon season, public procurement system prioritizing rice over maize, subsidized or free electricity for irrigation, limited drying facilities for maize grains, inadequate marketing support for mungbean, and lack of access to CA-based machinery such as the happy seeder and multi-crop bed planters. If effective policy interventions successfully encourage Indian farmers to adopt intensified and diversified practices in the traditional MW cropping system, for instance, incorporating mungbean in 50% of the existing area (a total of 1.86 million hectares), it has the potential to address the protein requirements of an additional 8.1 million malnourished individuals annually (Parihar et al. 2017). This underscores the significance of policymakers' role in

promoting and facilitating sustainable agricultural practices to alleviate malnutrition and enhance regional food security.

Environmental degradation can largely be attributed to the failure of agricultural commodity markets to factor in environmental costs stemming from unsustainable land use and their associated effects (Lant et al. 2008). An effective strategy is to integrate the environmental benefits associated with the adoption of sustainable management practices and crop diversification into economic incentive schemes (Bryan 2013). These schemes are increasingly being promoted to bring about favorable changes in land use and management, thereby stimulating the provision of ecosystem services from agroecosystems. To harness the benefits of emerging carbon credits, financial incentives can be given to farmers to encourage them to diversify their cropping patterns, thereby creating markets for alternative crops. In this context, few efforts are made in IGP, such as “Pani Bachao Paise Kamao” scheme was implemented in 2018 to prevent groundwater overexploitation due to paddy cultivation in Punjab. In Haryana state in 2020, Rs 7000 per acre to farmers for diversifying more than 50% of their Kharif season paddy. Similarly, in Punjab, Rs 7000 per acre for shifting from paddy to alternative crops, with Rs 2.9 billion allocated for the financial year 2024–2025 under the crop diversification program (Rautaray and Sucharita 2024). The government of Punjab also announced an incentive amount of Rs 1500 per acre for the farmers sowing the paddy directly (without transplanting) during 2023–2024.

Climate change

Climate change poses a significant threat to agriculture and food security, particularly in India where the sensitivity to monsoon variability makes the agriculture sector highly vulnerable. Recent events, such as the 112% more rainfall than the average in July 2023, resulting in disastrous flash floods in NW India, highlight the increasing risks posed by climate change (Guardian 2023). Projections indicate that the IGP region, which is prone to extreme weather events, may experience a decline in crop yields ranging from 10 to 40% by 2050 with a higher risk of even crop failures (Kakraliya et al. 2018). Furthermore, it is estimated that by the year 2050, around 51% of the IGP may become unsuitable for growing wheat, which is an important staple crop for food security in India, primarily due to escalating heat stresses (Lobell et al. 2012). On the other hand, the intensification of irrigation in the IGP in recent decades can have a strong impact on the regional climate by reducing precipitation from June to September, as well as having global implications. Therefore, adapting to climate change is not a choice but a necessity to mitigate the adverse impacts and reduce vulnerability.

Adopting climate-smart agricultural practices (CSAPs), including components of CA, tailored to different aspects

of crop production, is crucial for sustainable farming and enhancing climate resilience. CSAPs relate to nutrients (e.g., soil plant analysis development (SPAD) chlorophyll meter, green seeker sensor, site-specific nutrient management (SSNM) or nutrient expert (NE), and soil-test crop response (STCR)), water (e.g., LLL, alternate wetting and drying, micro-irrigation, and weather forecast-based irrigation), carbon (e.g., residue retention and incorporation), extreme weather (index based crop insurance), energy (e.g., LLL and ZT), and information and communication technologies (ICTs) (Kakraliya et al. 2018). However, the effectiveness of specific crop establishment practices may vary across agroecological conditions and depend on factors such as rainfall patterns. For example, the annual precipitation in the IGP region varies widely, ranging from less than 400 mm in western IGP (Pakistan) to over 1600 mm in eastern IGP (east India and Bangladesh) (White and Rodriguez 2008). Therefore, by evaluating various options and tailoring CSAPs to their specific local conditions and requirements, farmers can enhance crop resilience to climate change, improve agricultural productivity, and promote sustainability.

Farmers' perceptions and belief

Farmers often rely on local retailers as sources of information and guidance regarding pesticide use, shaping their perceptions and decisions. Similarly, farmers' beliefs about fertilizer practices contribute to the issue of excessive fertilization, as many believe that increasing fertilizer applications always leads to higher crop yields. Disseminating knowledge to challenge this belief and highlight the associated negative effects is a challenging task to promote the balanced use of fertilizers and pesticides. For instance, Birkenholtz (2017) noted that farmers are inclined to adopt drip irrigation primarily to boost their income rather than to save groundwater, and the saved water is used to expand the irrigated area or opt for more water-intensive crops, resulting in seemingly no effects on groundwater depletion.

Transitioning from conventional practices to CA practices necessitates profoundly transforming farmers' conservative mindsets and beliefs. The social networks of farmers, primarily consisting of peers with similar landholding categories, play a crucial role in shaping their perceptions. Consequently, exposure visits and on-farm experiments are vital for influencing and enhancing farmers' adoption of new practices. Furthermore, active participation from state governments and stakeholders is crucial in implementing a participatory system that empowers farmers by providing them with the right equipment and training to explore the new technologies, allowing them to determine their effectiveness and identify any necessary feedback for large-scale adoption (Mishra et al. 2022). Such enabling initiatives can address the behavioral aspects of irrigation, nutrient, and pesticide

management and promote knowledge sharing within farming communities for desired outcomes.

Conclusion and policy implications

This study explored the diverse facets of sustainable management practices within RW cropping systems, with a specific focus on groundwater resources and soil health. Given the alarming rates of groundwater depletion and soil degradation resulting from excessive groundwater withdrawal and fertilizer and pesticide application, urgent action toward sustainable agricultural management is imperative. The following are actionable insights for policy implications for policy planners and other stakeholders for sustaining natural resources and production systems, thereby achieving national goals (e.g., higher farm income and welfare, diversification) and international commitments (e.g., land degradation neutrality and sustainable development goals). Key policy implications are as follows:

- (a) An integrated and holistic approach, combining appropriate supply-side solutions (such as groundwater recharge augmentation and rainwater harvesting) and demand-side solutions (such as promoting micro-irrigation, crop diversification, and increasing water-use efficiency), needs to be formulated. Concerted efforts should be made for its large-scale adoption, with adequate support of knowledge sharing, capacity building programs, and financial help coupled with enabling policy environment to increase the sustainability of groundwater resources.
- (b) Adoption of conservation agriculture enhances productivity, profitability, and resilience; however, limited access to CA technologies, particularly by resource-poor farmers, is a barrier to realizing its potential benefits. Therefore, synergetic efforts should be made for its widespread adoption by addressing the issues and problems that hinder access to CA-based technologies. For example, establishing dedicated government/cooperative bodies, such as those providing zero-till drill services and micro-irrigation innovations, can significantly boost adoption rates.
- (c) Real-world agricultural systems are more complex than experimental settings, necessitating cautious interpretation of study results and consideration of multiple agroecological processes, scales, and contextual interactions between them. Therefore, technologies must be tailored to specific sites, taking into account soil conditions, agro-climatic conditions, and socioeconomic factors before advocating as RCT/CA practice for a region.
- (d) The development of efficient direct seeding machines, such as the Happy Seeder, Super Seeder, and compat-

ible tractors will facilitate wheat sowing even under heavy residue retention conditions, making it economically viable for small and marginal farmers. Additionally, implementing superior straw management systems, enforcing strict laws and fines for residue burning, promoting in situ crop residue decomposition through chemical, biological, or mechanical methods, and subsidizing the cost of machinery for residue incorporation will help eliminate the need for rice residue burning, thereby enhancing the sustainability of the system.

- (e) Prolonged pesticide presence in soil intensifies shifts in microbial populations, underscoring the need for comprehensive research on ecological implications along with policy and institutional interventions, particularly mandating rigorous testing before their commercial uses and creating awareness about integrated pest management.
- (f) Farmers must be encouraged for precision and site-specific use of nutrients and recommended application of pesticides; for this, the focus should be on capacity-building programs to improve farmers' understanding in terms of hazardous effects on human health and associated environmental risks of indiscriminate use of fertilizers and pesticides, thus promoting judicious use of agrochemicals.
- (g) Empowering farmers with knowledge and skills is pivotal for promoting efficient and sustainable agricultural practices. To this end, extension agencies and other stakeholders should prioritize strengthening environmental awareness programs through diverse media platforms and engaging activities such as exposure visits, field demonstrations, and tailor-made training programs.
- (h) With the increasing use of economic incentives for conservation programs, it is suggested that these mechanisms must be internalized to compensate farmers for potential losses (if any, during the initial phase of adoption) associated with the adoption of resource conservation technologies and to reward the ecosystem services (cost reductions, improved quality, increased production, carbon credits, and higher prices for safe produce) generated by the adoption of sustainable practices.
- (i) Lastly, farmers should be educated about avoiding their too dependence on public-funded schemes, which often lead to sub-optimal outcomes due to a lack of comprehensiveness and holistic aspects, and therefore fail to provide solutions for complex socio-economic and environmental issues. Therefore, there is a need to explore innovative business models and public-private partnerships (PPP), which could be viable options for achieving environmental sustainability. Overall, it can

be suggested that there is a need to develop location-specific needs and priority-based plans by factoring in the socioeconomic endowments and adequately addressing the hindrances faced by farmers in natural resource management, thereby ensuring the food, nutrition, livelihood, and environmental security of the region.

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Author contribution S.S. conceptualized the design of the study, analyzed the data, and wrote the original draft. J.V.D., C.R., A.S., S.K.1, S.K.2, with S.K.1 chosen because this name is furthest up the author list, and D.S.B. contributed to the design of the study and reviewed and edited the paper. All authors read and approved the final manuscript.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper, particularly in the subsection "Data sources" of the "Methodology and data" section and its supplementary information file.

Declarations

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Consent to participate Not applicable.

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