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

Shailendra Singh Shah
shailendra.shah@wur.nl

Wageningen University & Research https://orcid.org/0000-0003-4157-7642
Jos van Dam
Wageningen University & Research
Awtar Singh
CSSRI: Central Soil Salinity Research Institute
Suresh Kumar
CSSRI: Central Soil Salinity Research Institute
Satyendra Kumar
CSSRI: Central Soil Salinity Research Institute
Devendra Singh Bundela
CSSRI: Central Soil Salinity Research Institute
Coen Ritsema
Wageningen University & Research

Research Article

Keywords: Irrigation, Nutrient, Pesticide, Soil Health, Groundwater, Agricultural sustainability, Environmental pollution

Posted Date: April 23rd, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4151237/v1

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, primarily driven by conventional cultivation practices, particularly the rice-wheat (RW) cropping system, which comprises 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, addresses challenges, and proposes sustainable management options to achieve development goals. Our district-wise analysis estimates potential water savings from 20–60% 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, greater 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.

1. 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 percent 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 7 fold, and expansion of irrigated land by two fold (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, precipitating 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 (Parihar et al., 2020; Sapkota et al., 2017), 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 (Fagodiya et al., 2023; Sapkota et al., 2017).

Conservation Agriculture (CA) is considered to be 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 (iii) diversification of crops (FAO, 2023). Numerous studies conducted in the NW IGP 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., 2018), improved soil microbial diversity and enzymatic activities through increased soil organic carbon (Parihar et al., 2020), suppress of soil evaporation, and attenuation of soil temperature and moisture variability (Singh & Sidhu, 2014), reduced air pollution from stubble burning (Jain et al,, 2018), and improve the overall physical, chemical, and biological properties of soils (Jat et al., 2019).

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 1 to 3 meters per year (Devineni et al., 2022). Moreover, some projections show if the mitigation efforts are not made then the groundwater depletion rates could be as high as 2.8 meters per year in certain areas by 2028 (Shekhar et al., 2020). Due to the substantial reliance of the RW system on GW for irrigation, it is typically held responsible for the over-exploitation of GW resources (Humphreys et al., 2010), raising questions about the sustainability of present agricultural practices. Thus, there is a pressing need to adopt water-saving technologies to enhance water productivity (crop yield per unit of water consumption) while sustaining GW levels and farming profitability. Water-saving technologies such as micro-irrigation (drip irrigation and sprinkler) and laser land leveling (LLL) demonstrated their effectiveness in field situations (Surendran et al., 2021; Brar et al., 2022). Most of the extant studies have evaluated the efficacy of resource conservation technologies at the field levels, assessing the effect of one technology at a time (Chakraborti et al., 2023; Devineni et al., 2022), without exploring the potential of switching to the CA-based RW system or the role of the bundle of resource conservation practices in sustainable management of scare GW resources, and other ecological issues of the region. 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, for effective and evidence-based policy communication, in this study, an attempt is made to assess and compare the effects of conventional practices vis-a-vis CA on multiple environmental indicators for the districts NWIGP, and provide actionable insights for stakeholders 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 increase to the tune of 95% as compared to 2000, while pesticide usage rose by 37% to 0.450 Mt during the same period (FAO, 2022). However, the continuous and excessive application of chemical fertilizers and pesticides has precipitated a host 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 (Rahman & Zhang, 2018; Guo et al., 2010; Mari et al., 2008). 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 & 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 & 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 GW resources.

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 status. 2) District-wise GW water-saving potential of transitioning from flood to drip irrigation, sprinkler systems, LLL, and CA. 3) The current status of fertilizer and pesticide management and their effects on soil properties, soil microflora, fertility, and groundwater resources.

2. Background

2.1. 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 (commonly known as soil puddling), followed by the transplantation of 25- to 30-day-old seedlings and maintaining a water depth of 2–3 inches for 30–40 days with irrigation resumed two days after the water recedes (Anonymous, 2020; Sidhu et al., 2019). This 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 h ha^{-1} time, and 2100–2400 MJ ha^{-1} energy, depending on the level of mechanization (Rashid et al., 2009; Verma & Dewangan, 2006). 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 (Kumar & Ladha, 2011; Sharma et al., 2003). 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 fifty percent of the applied nitrogen (Singh & 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 & 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 & Ladha, 2011; Sharda et al., 2017). Studies by Sharma et al. (2018) and Kumar et al. (2011) have also found 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 (Jat et al., 2020; Chauhan & Opeña, 2012; Kumar & Ladha, 2011).

2.2. 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) 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 towards bolstering national food security (Handral et al., 2017). Notably, district-level analyses reveal nuanced variations, with Punjab and Haryana witnessing significant expansions in rice cultivation, while Uttar Pradesh experiences pronounced growth in wheat acreage (Fig. 2). Despite intermittent challenges stemming from climatic fluctuations, labor shortages, and environmental degradation, the overall trajectory of the RW system in NWIGP has been characterized with impressive growth. Understanding these trends provides crucial insights for policymakers, researchers, and agricultural stakeholders to develop regional strategies for sustainable agriculture.

2.3. 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 NW IGP, 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 upsurge 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 from 1.076 Mt and 0.275 Mt in 1990 to 2.603t (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-20th 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.

2.4. 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 rampant 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 (CGWB, 2019).

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 10m in dug wells and 25m 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 pictured, elucidating the interplay between water demand, extraction practices, and hydrogeological factors, indispensable for formulating effective strategies for sustainable GW management.

2.5. Soil fertility

A prevalent deficiency of both macro-nutrients (N, P, K) and micro-nutrients is evident in Indian soils (Shivay et al., 2019), raising significant concerns regarding agricultural sustainability. Soil fertility degradation stems from nutrient depletion due to intensive crop cultivation and residue burning. For instance, a RW rotation yielding 7 t ha^{-1} of rice and 4 t ha^{-1} of wheat removes over 300 kilogram (kg) N, 30 kg P, and 300 kg ha^{-1} K from the soil (Singh & Singh, 2008). Additionally, burning crop residues leads to the loss of 80% of N, 25% of P, and 20% of K present in straw (Jain et al., 2018). Pathak's (2010) analysis of soil fertility trends 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. Understanding soil nutrient deficiencies is pivotal for sustainable crop production.

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, 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, with fertilizer application following soil testing 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.

3. Methodology and data

3.1. 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 NW IGP. SLRs are recognized as a reliable and less biased approach to conducting reviews, enabling the formulation of evidence-based conclusions (Koutsos et al., 2019). In contrast to traditional review methods, SLRs offer a higher level of reliability and minimize biases in the analysis (Koutsos et al., 2019). There are different approaches to conducting systematic reviews. In this study, the SLR method, PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis), was employed (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 the following sections.

3.1.1. Information sources and search strategy

A comprehensive literature search was conducted using two specialist peer-reviewed publication databases: Web of Science and Scopus. These databases were selected for their extensive coverage and inclusion of the most current interdisciplinary academic publications. To ensure the inclusivity of all relevant research, a search without a specific start year was conducted and continued until June 1, 2023. The database searches were conducted in English using broad terms such as "Western Gangetic Plain (equivalent to Northwestern Indo-Gangetic Plain) AND Irrigation OR Nutrient OR Pesticide" (Table S1). A total of 187 articles were obtained, including peer-reviewed publications and grey literature such as conference proceedings, working papers, and project reports, with 94 from Web of Science and 93 from Scopus. All bibliographic details were managed using Endnote (https://endnote.com) to handle references. The first screening stage involved eliminating any duplicated publications, leaving 111 articles for further evaluation (Fig. S1).

3.1.2. Selection and eligibility criteria

This paper used strict eligibility criteria to select relevant articles addressing the scope of the research. The predetermined inclusion and exclusion criteria utilized in this study are presented in Table S2. Information from sources unrelated to water, nutrient, and pesticide management was excluded from the analysis. Furthermore, articles focusing on study areas outside the NW IGP were also excluded. Among the potential articles, 80 peer-reviewed articles met the initial criteria. However, during the thorough reading of the main body content, 7 articles were identified as not related to agricultural practices and were subsequently discarded. As a result, the final review consisted of 73 articles for data synthesis and analysis (Table S3).

3.1.3. Data extracting and summarizing

The data obtained through in-depth reading of the final set of articles were recorded in an MS Excel spreadsheet. The selected studies were coded and categorized into different thematic groups based on specific details. These categories included the research focus, geographical location, crop of interest, 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.

3.2. Data

3.2.1. Data sources

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 levels 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 Indian Meteorological Data (IMD).

3.2.2. Groundwater irrigation extraction

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

$$\mathrm{GW_{ext}} = \mathrm{WC_{irr}} \times \mathrm{GW_{frac}}$$

1

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

The district-wise seasonal water consumption through irrigation ($\mathrm{WC_{irr}}$) 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.

$$\mathrm{WC_{irr}} = c_{\mathrm{i,irr}} \times d_i$$

2

Here, $c_{i,irr}$ 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 1. For, CA, a reduction of 40% in water use is assumed based on a literature review.

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

$$\mathrm{GW_{frac}} = \frac{\mathrm{Area_{irr,GW}}}{\mathrm{Area_{irr,GW}} + \mathrm{Area_{irr,SW}}}$$

3

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

Table 1
Seasonal irrigation water consumption is based on Fisherman 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

4. Impact on groundwater resource

4.1. Irrigation management

Conventional rice cultivation is water-intensive as 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 (Jat et al., 2009; Kahlown et al., 2007; 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 (Kahlown et al., 2007). Notably, Kahlown 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 25–80% with the adoption of DI has been reported (Joseph et al., 2022). Furthermore, sub-surface drip irrigation (SSDI) in rice-based systems can save up to 61% more water over FI (Sandhu et al., 2019; Soman et al., 2018). 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, reduced evaporation, and deep drainage losses (Sidhu et al., 2019). Furthermore, DI reduces weed growth by 43–95% (especially *Phalaris minor*) and enhances nitrogen-use efficiency by 20% compared to FI (Jat et al., 2021).

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 and GW recharge potential with Permanent Bed (PB) systems. 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 Jat et al. (2020) and Sharma et al. (2018), 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.

4.2. 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 higher recharge; however, the prevalence of rice cultivation impedes water percolation to lower soil layers, hindering recharge potential (Joseph et al., 2022). 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. 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 (Joseph et al., 2022; Sharda et al., 2006).

Adoption of drip irrigation can substantially reduce the decline in GW levels. Model analysis by Sishodia et al. (2018) suggests that converting to DI can mitigate GW decline during rainfall deficit years. Similarly, Joseph et al. (2022) indicated the reduction in GW depletion in Punjab and Haryana, although it does not alter the overall trend of groundwater level decline. Additionally, 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, the trend of groundwater decline cannot be reversed. 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.

4.3. 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 reduced return flow (Chakraborti et al., 2023). Therefore, sustainable water management in such regions will necessitate complementary approaches, such as switching cropping patterns towards 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, has shown promise in reducing GW depletion rates, as evidenced in Punjab (Russo et al., 2015). 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 switching from flood to drip irrigation and altering crop practices can lead to a substantial improvement, with a 78% reduction in GW depletion observed 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.

5. Impacts of Chemical Fertilizers and Pesticides

The pivotal role of fertilizers and pesticides in agriculture is undeniable, yet with increasing awareness of their impacts, it’s crucial to assess their impact on soil and water, emphasizing the need for sustainable farming practices (Hossain et al., 2022). While chemical fertilizers and pesticides serve to enhance plant growth and boost yields over relatively short periods, their excessive use poses potential risks and adverse effects on the agroecosystem (Baweja et al., 2020). For instance, only 0.1% of applied pesticides effectively reach the target organism, with the majority contaminating soil and water environments (Mandal et al., 2019). On the other hand, nitrogenous fertilizers applied for crop growth result in a substantial loss of nitrogen to groundwater water through leaching (Verma et al., 2023). Therefore, this section critically examines current practices in nutrient and pesticide management and their potential implications on soil health and groundwater resources.

5.1. Status of fertilizer and pesticide management

Rice and wheat use about 53% of India’s total fertilizer N usage (FAO, 2022). In 2000, diagnostic surveys disclosed that farmers applied greater than recommended N doses (130 to 195 kg N ha^{-1}), less P (11–14 kg ha^{-1}), and limited K to rice in the NWIGP (Yadav et al., 2000). Later, Singh et al. (2013) and Kakraliya et al. (2018) corroborated these findings within the IGP. In wheat, the common practice involves using 95–200 kg N ha^{-1} and 13–24 kg P ha^{-1} (Singh & Singh, 2012). Farmers frequently apply more N than is recommended because of their improper application practices (Fagodiya et al., 2023). Similarly, Shivay et al. (2019) revealed that farmers predominantly apply N and P, without due consideration of micronutrients and other secondary nutrients. Furthermore, the practice of residue burning exacerbates soil nutrient depletion and leads to multiple nutrient deficiencies, ultimately impacting crop productivity (Bhatt et al., 2021; Biswakarma et al., 2022).

Recommended fertilizer doses of NPK differed among the articles in the NW IGP. Table 2 presents the fertilizer doses recommended by various researchers. The usual practice is to apply the total recommended doses of P and K and half or 2/3rd of the total N through urea (46% N), single superphosphate (46% P_2O_5), and muriate of potash (60% K_2O), respectively, before sowing. The remaining N will be used in two halves during tillering and panicle initiation stages or three splits depending on the sensitive stages of crops (Jat et al., 2020; Thind et al., 2017). Farmers of RW in the IGP barely use recommended dosages of fertilizers (Singh & Singh, 2012). The reluctance to adopt recommended practices may stem from a lack of understanding of the instructions or information, elevated costs of recommended fertilizer mix, and the absence of technical guidance (Fishman et al., 2016).

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 & Opeña, 2012). In certain locations in Haryana, farmers exceeded the recommended herbicide dosage by 3–4 times during the 2017-18 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 3. For example, Singh et al. (2011) recommended using pendimethalin @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 (Gora et al., 2022; Jat et al., 2020). 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's noteworthy that while most studies focus on herbicides[2], our emphasis in the following sections will be more on insecticide and fungicide use.

Table 2
The recommended dose of fertilizer for rice and wheat in the NW IGP

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 & 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., 2018; 2023)
150: 26: 25 N: P: K kg ha^{-1}	Wheat	PAU, Punjab	Saikia et al. (2019)

Table 3
Pesticide management in rice and wheat in the NW IGP

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 wedding 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)

5.2. Impacts on soil health

The prolonged and intensive application of chemical fertilizers and pesticides in the soil can have diverse effects on soil health (Baweja et al., 2020; Prashar & Shah, 2016). 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 (soil texture, bulk density, and water holding capacity) (Larson & Pierce, 1994). These parameters are interconnected and exert mutual influence. Excessive fertilizer use poses various risks to soil health, including soil acidification, compaction, erosion, runoff, contamination, altered enzymatic activities, and a decline in organic matter content (Pahalvi et al., 2021; Rahman & Zhang, 2018). Additionally, residue burning leads to a complete loss of organic C and N and, a 20–25% loss of P and K (Singh et al., 2014). Conversely, pesticides persist in the soil for extended periods, forming transformation products with toxic effects, hindering enzyme activities, and reducing soil biodiversity (Hossain et al., 2022). Therefore, this section presents the impact of fertilizers and pesticides on soil properties, soil microflora, and fertility.

5.2.1. Soil properties

Intensive fertilizer application has been shown to impact soil properties significantly, affecting soil organic carbon (SOC) content, nitrogen level, and soil pH (Rahman & Zhang, 2018; Savci, 2012). Nitrogen compounds such as ammonium ion, nitrate ion, and urea are known to alter soil pH levels, potentially enhancing the availability of heavy metals in the soil; for example, cadmium (Cd) through phosphate fertilizer (Huang & Jin, 2008). 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). A study by Guo et al. (2010) reported severe soil acidification and reduced productivity with the excessive application of synthetic fertilizer. Soil compaction, resulting from various factors such as reduced organic fertilizer usage, heavy machinery use, acidification, and continuous plowing at a consistent depth, poses numerous challenges including inadequate aeration, increased bulk density, reduced permeability, erosion, runoff, and soil degradation (Batey, 2009; Mari et al., 2008). Research by Singh et al. (2014) found 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. This parallel outcome is echoed by (Yang et al., 1999), supported by extensive 16-year research. Moreover, repeated burning in RW reduces mineralizable N and C in the 0–15 cm soil layer, thereby negatively affecting organic matter mineralization and nutrient cycling (Jain et al., 2018).

SOC, a vital indicator of soil health, profoundly influences the physical, chemical, and biological properties of soil. Inorganic N fertilizer application can intricately alter carbon dynamics in soil, impacting the decomposition and mineralization of organic matter. Moreover, pesticide retention correlates directly with soil organic matter 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 Biswakarma et al. (2022) and Das et al. (2013) reported a 15–24% higher total SOC stock under CA compared to CT in the RW system. Singh et al. (2014) recorded a significant increase of 19.04, 34.73, and 38.77% in SOC under ZT over 15 years in sandy loam, loam, and clay loam soil, respectively. Moreover, the inclusion of mungbean in RW increased SOC by 83% over the RW system (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).

5.2.2. Soil Microflora and fertility

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 (Prashar & Shah, 2016; Islam et al., 2009). Furthermore, synthetic chemicals inhibit nitrogen-fixing rhizobia bacteria, leading to disruptions in nutrient cycling processes and ultimately increasing dependency on synthetic fertilizers (Rahman & Zhang, 2018). Additionally, pesticide applications have led to a shift of plant-parasitic nematodes while reducing beneficial bacteria and fungi-feeding nematodes, vital for organic matter decomposition and biological control (Yardirn & 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 & D’Souza, 2010). 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 (Martınez-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 & 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.

The activities of various soil enzymes, such as alkaline phosphatases, dehydrogenase, proteases, ureases, and *ß*-glucosidases, are crucial indicators of microbial activity 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 *ß*-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 PB and ZT, enzymatic activities including dehydrogenase, fluorescein diacetate, and *ß*-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).

5.3. 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 & 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 & 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, BHC, Aldrin, Dieldrin, Heptachlor) in UP (Kaushik et al., 2012; Singh et al., 2005). 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 kg/ha to 160 kg/ha) (Verma et al., 2023), underlining the importance of similar regulations and continuous evaluation to combat groundwater pollution, especially in severely affected regions like the NWIGP.

6. Challenges and Opportunities

6.1. Sustainable intensification and diversification

Sustainable intensification coupled with diversification, based on the CA practices is crucial to satisfy the growing populations' nutritional needs, ensuring food security, and minimizing negative environmental impacts while enhancing resource use efficiency. For instance, the use of maize instead of rice requires 80–85% less water and exhibits higher water productivity of 8–22 times than rice (Gathala et al., 2013; Jat et al., 2020; Kumar, 2018). Furthermore, the inclusion of mungbean in the maize-wheat (MW) systems resulted in a 38% higher system productivity, water savings of 1660 mm, and increased total water productivity by 270% compared to the PTR (Choudhary et al., 2018). The implementation of multiple cropping systems like summer mung bean-maize-wheat, supported by subsurface drip irrigation techniques, has the potential to achieve a 30% reduction in irrigation water usage (Brar et al., 2022). Furthermore, CA-based maize-chickpea-sesbania and maize-wheat-mungbean cropping systems registered 35-38.7% higher maize grain yield than the conventional practices (MW system) (Yadav et al., 2015).

Sustainable intensification and diversification of cereal systems are not only limited to improving crop, water, and nutrition productivity but also contribute to the improvement of soil and environmental health. The incorporation of mungbean in cereal systems has been shown to have beneficial impacts on soil physico-chemical properties as well as biological properties due to greater C addition and increases in both C-cycle and N-cycle enzyme activities (Das et al., 2021; Jat et al., 2020). Furthermore, Studies conducted by Bhatt et al. (2016) and Yadav et al. (2015) have demonstrated increased uptake of NPK nutrients when legumes are incorporated into cereal systems, contributing to the sustainability of cropping systems. Consequently, changes in cropping systems have profound effects on soil properties, nutrient availability, and overall soil quality in arid and semi-arid ecosystems (Khedwal et al., 2023). Furthermore, it leads to a reduction in weed density, with a decrease of 65% under ZT and 41% under CT (Weisberger et al., 2019). Adding leguminous crops in rice-wheat systems has been identified as an effective strategy for suppressing annual weeds such as *P. minor* and *A. arvensis* (Jat et al., 2021; Shahzad et al., 2016).

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, lack of access to CA-based machinery such as the happy seeder and multi-crop bed planters (Choudhary et al., 2018). Furthermore, effective policy interventions that successfully encourage Indian farmers to adopt intensified and diversified practices in the traditional MW cropping system, incorporating mungbean in 50% of the existing area (total of 1.86 million hectares), have 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 et al., 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, IGP few efforts are made, such ‘Pani Bachao Paise Kamao’ scheme was implemented in 2018 to prevent groundwater overexploitation due to paddy cultivation in Punjab. Similarly, in Haryana state in 2020, Rs 7000 per acre to farmers for diversifying more than 50% of their kharif season paddy (Rautaray et al., 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 2023-24.

6.2. 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 and a yearly negative nutrient balance of 8–10 tonnes (GOI, 2018). In the majority of soils, the SOC, which is vital for sustaining soil physical, chemical, and biological properties, is relatively low, often around 0.5%. These facts indicate the urgent need to revise existing land management practices to focus on soil health preservation and enhancement. However, 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 (Verma et al., 2023).

Soil contamination by pesticide residues is a major issue due to the persistent nature of pesticides and their potential toxicity to humans (Bhandari et al., 2020). 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). Similarly, in Nepal, around 60% of soil samples showed the presence of pesticides, with 25% having a single residue and 35% containing mixtures of two or more residues in 39 different pesticide combinations (Bhandari et al., 2020). However, such studies in India are scarce, highlighting the need to assess pesticide residues and their potential risks to the environment and ecosystem services.

6.3. Groundwater management

In Punjab and Haryana, about 92–96% of groundwater withdrawal is used for irrigation purposes (Dhanda et al., 2022). However, the extensive dependence on groundwater and insufficient availability of alternative infrastructure in the NW IGP has led to a steady decline in groundwater levels (Bhatt et al., 2021). Alarming estimates from the Central Ground Water Board (CGWB) indicated that out of the 138 blocks monitored in Punjab, approximately 80% were classified as overexploited (CGWB, 2019). Likewise, in Haryana, around 61% of the blocks were identified as overexploited, with only 20% classified as safe (Fig. 6g). The adverse effects of declining groundwater resources extend to the reduction of baseflow of major rivers in India, which is experiencing a reduction at a rate of approximately 0.30 ± 0.07 cm $year^{-1}$ or 2.39 ± 0.56 km^3 $year^{-1}$ (Mukherjee et al., 2018). The provision of free electricity for the agricultural sector further exacerbates this situation. The increasing depth of the groundwater table in NW IGP has several negative consequences. Firstly, it leads to higher pumping costs as traditional centrifugal pumps prove inadequate, necessitating 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, potentially rendering the groundwater unusable due to the upward movement of salts from the deeper groundwater and the intrusion of saline water into fresh groundwater (Bhatt et al., 2016).

Groundwater irrigation through electric tubewells is dominant, with 72% of the total tube-well 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 (Khedwal et al., 2023). 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 & 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).

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 (Srivastava et al., 2017). Despite the low adoption rates of drip and sprinkler irrigation in IGP (only 0.1–2.5%), these proven technologies have the potential to halve unsustainable over-extraction of groundwater, particularly in NWIGP (Joseph et al., 2022). However, efforts are needed to overcome the high installation cost of SSDI which hinders their widespread adoption. Additionally, the introduction of incentives and metered tariff policies for groundwater conservation and electricity used for pumping with regular monitoring of groundwater level. It is essential to recognize that technology adoption and demand-side management alone may not suffice to stabilize water tables, warranting consideration of supply-side management strategies such as artificial recharge (Fishman et al., 2015; Sharda et al., 2006). Therefore, comprehensive policy interventions encompassing water pricing, infrastructure development, awareness programs, restoration of canal water supply, increased aquifer recharge, and promotion of sustainable water management practices for the long-term sustainability of groundwater in the region.

6.4. 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 (Agrawal et al., 2019). 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, and soil-test crop response (STCR)), water (e.g. LLL, alternate wetting and drying, drip 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) (Jat et al., 2019; 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 & 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.

6.5. 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. 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 (Chakraborti et al., 2023). This paradigm shift requires farmers to embrace new approaches and challenge long-held practices (Mishra et al., 2022). 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 (Kassam et al., 2015). Such enabling initiatives can address the behavioral aspects of irrigation, nutrient, and pesticide management and promote knowledge sharing within farming communities for desired outcomes.

7. 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 fertilizer and pesticide application, urgent action toward sustainable agricultural management is imperative. 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, etc.) and international commitments (e.g., Land Degradation Neutrality and Sustainable Development Goals). Key policy implications are as follows: (a) An integrated and holistic approach with appropriate supply (augmentation of groundwater recharge, rainwater harvesting, etc.) and demand-side (promotion of micro-irrigation, crop diversification, increase in water-use efficiency, etc.) solutions need to be formulated, and concerted efforts are to be made for its large-scale adoption, with adequate support of knowledge sharing, capacity building programs, and financial help coupled with enabling policy environment; (b) Adoption of conservation agriculture enhances productivity, profitability, and resilience; however, limited access to CA technologies, particularly by resource-poor farmers, is a barrier in realizing its potential benefits. Therefore, concerted efforts should be made for its widespread adoption by addressing the issues and problems that hinder access to CA-based technologies; (c) 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 of mandating rigorous testing before their commercial uses, creating awareness about integrated pest management, and promoting approved doses and formulations; (d) Farmers must be encouraged for precision and site-specific use of nutrients and, and recommended application of pesticides, for this, 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, and thus promoting judicious use of agrochemicals; (e) 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; (f) With the increasing use of economic incentives for conservation programs, it is suggested that economic incentive 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. (g) Lastly, farmers should be educated about avoiding their too dependence on public-funded schemes, which often lead to sub-optimal outcomes due to 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.

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
PB	Permanent Bed
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

Declarations

Funding

This work is supported by the Dutch Research Council, Government of The Netherlands, through the Meridian Fund (project no. 482.20.303) and by the Department of Science & Technology, Government of India (project no. DST/TMDEWO/WTI/NWO/CGAW/2020/14), under the jointly funded Cleaning the Ganga and Agri-Water initiative and the Hindon Roots Sensing project: *River Rejuvenation through Scalable Water- and Solute Balance Modelling and Informed Farmers' Actions.*

Acknowledgment

We are thankful to the Soil Physics and Land Management group, Wageningen University & Research, and ICAR-Central Soil Salinity Research Institute for making necessary arrangements during the review process. We would like to express our gratitude to Dr. Sudhir Kumar Goel and Mr. Bastiaan Mohrmann for their valuable feedback and support during the review process. The authors thank the anonymous reviewers for their constructive comments.

Author Contributions

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.

Ethics declarations

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

References

1. Agrawal, S., Chakraborty, A., Karmakar, N., Moulds, S., Mijic, A., & Buytaert, W. (2019). Effects of winter and summer-time irrigation over Gangetic Plain on the mean and intra-seasonal variability of Indian summer monsoon. *Climate Dynamics*. https://doi.org/10.1007/s0038 2-019-04691-7
2. Ahada, C., & Suthar, S. (2018). Groundwater nitrate contamination and associated human health risk assessment in southern districts of Punjab, India. *Environmental Science and Pollution Research*, *25*, 25336–25347.

3. Anonymous. (2020). Package of Practices for Kharif Crops, Punjab Agricultural University, Ludhiana. *9*.
4. Aryal, J. P., Mehrotra, M. B., Jat, M. L., & Sidhu, H. S. (2015). Impacts of laser land leveling in rice–wheat systems of the north–western indo-gangetic plains of India. *Food Security*, *7*(3), 725-738. https://doi.org/10.1007/s12571-015-0460-y
5. Barreiro, A., Martin, A., Carballas, T., and Diaz-Ravina, M. (2016). Long-term response of soil microbial communities to fire and fire-fighting chemicals. *Biol Ferti Soils*, *52*, 963–975.
6. Batey, T. (2009). Soil compaction and soil management–a review. *Soil use and management*, *25*(4), 335-345.
7. Baweja, P., Kumar, S., Kumar, G. (2020). Fertilizers and Pesticides: Their Impact on Soil Health and Environment. In B. Giri, Varma, A (Ed.), *Soil Health*, 59. *Soil Biology*. https://doi.org/10.1007/978-3-030-44364-1_15
8. Bhandari, G., Atreya, K., Scheepers, P. T. J., & Geissen, V. (2020). Concentration and distribution of pesticide residues in soil: Non-dietary human health risk assessment. *Chemosphere*, *253*.
9. Bhardwaj , A. K., Pandiaraj T, Chaturvedi, Sumit, Singh, T.C, Soman P., Bhardwaj A.K. and Labh B. . (2018). Growth, Production Potential and Inputs Use Efficiency of Rice under Different Planting Methods in Drip Irrigation. *Current Journal of Applied Science and Technology*, *26*(6), 1-9.
10. Bhatt, R., Kukal, S. S., Busari, M. A., Arora, S., & Yadav, M. (2016). Sustainability issues on rice–wheat cropping system. *International Soil and Water Conservation Research*, *4*(1), 64-74. https://doi.org/10.1016/j.iswcr.2015.12.001
11. Bhatt, R., Singh, P., Hossain, A., & Timsina, J. (2021). Rice-wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. *Paddy and Water Environment*, *19*(3), 345-365. https://doi.org/10.1007/s10333-021-00846-7
12. Bhattacharyya, R., Das, T. K., Sudhishri, S., Dudwal, B., Sharma, A. R., Bhatia, A., & Singh, G. (2015). Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. *European Journal of Agronomy*, *70*, 11-21. https://doi.org/10.1016/j.eja.2015.06.006
13. Birkenholtz, T. (2017). Assessing India’s drip-irrigation boom: efficiency, climate change and groundwater policy. *Water International*, *42*, 663–677.
14. Biswakarma, N., Pooniya, V., Zhiipao, R. R., Kumar, D., Shivay, Y. S., Meena, M. C., Lama, A., Das, K., Jat, R. D., Puniya, M., & Babu, S. (2022). Designing resource efficient integrated crop management modules for direct seeded rice-zero till wheat rotation of north western India: Impacts on system productivity, energy-nutrient-carbon dynamics. *Archives of Agronomy and Soil Science*, *69*(8), 1236-1250. https://doi.org/10.1080/03650340.2022.2079635
15. Biswakarma, N., Pooniya, V., Zhiipao, R. R., Kumar, D., Verma, A. K., Shivay, Y. S., Lama, A., Choudhary, A. K., Meena, M. C., Bana, R. S., Pal, M., Das, K., Sudhishri, S., Jat, R. D., & Swarnalakshmi, K. (2021). Five years integrated crop management in direct seeded rice–zero till wheat rotation of north-western India: Effects on soil carbon dynamics, crop yields, water productivity and economic profitability. *Agriculture, Ecosystems & Environment*, *318*. https://doi.org/10.1016/j.agee.2021.107492
16. Bora, K. (2022). Spatial patterns of fertilizer use and imbalances: Evidence from rice cultivation in India. *Environmental Challenges*, *7*, 100452. https://doi.org/10.1016/j.envc.2022.100452
17. Brar, A. S., Kaur, K., Sindhu, V. K., Tsolakis, N., & Srai, J. S. (2022). Sustainable water use through multiple cropping systems and precision irrigation. *Journal of Cleaner Production*, *333*. https://doi.org/10.1016/j.jclepro.2021.130117
18. Bryan, B. A. (2013). Incentives, land use, and ecosystem services: Synthesizing complex linkages. *Environmental science & policy*, 27, 124-134.
19. CGWB. (2019). Ground Water Year Book, *Department of Water Resources, River Development and Ganga Rejuvenation, New Delhi*.
20. Chakraborti, R., Davis, K. F., DeFries, R., Rao, N. D., Joseph, J., & Ghosh, S. (2023). Crop switching for water sustainability in India’s food bowl yields co-benefits for food security and farmers’ profits. *Nature Water*, *1(10)*, 864-878. https://doi.org/10.1038/s44221-023-00135-z
21. Chauhan, B. S., & Opeña, J. (2012). Effect of tillage systems and herbicides on weed emergence, weed growth, and grain yield in dry-seeded rice systems. *Field Crops Research*, *137*. https://doi.org/10.1016/j.fcr.2012.08.016
22. Choudhary, M., Jat, H. S., Datta, A., Yadav, A. K., Sapkota, T. B., Mondal, S., Meena, R., Sharma, P. C., & Jat, M. (2018). Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. *Applied Soil Ecology*, *126*, 189-198. https://doi.org/10.1016/j.apsoil.2018.02.027

23. Dangar, S., Asoka, A., & Mishra, V. (2021). Causes and implications of groundwater depletion in India: A review *Journal of Hydrology 596*, 126103. https://doi.org/10.1016/j.jhydrol.2021.126103
24. Das, S., Bhattacharyya, R., Das, T. K., Sharma, A. R., Dwivedi, B. S., Meena, M. C., Dey, A., Biswas, S., Aditya, K., Aggarwal, P., Biswas, A. K., & Chaudhari, S. K. (2021). Soil quality indices in a conservation agriculture based rice-mustard cropping system in North-western Indo-Gangetic Plains. *Soil & Tillage Research*, *208*. https://doi.org/10.1016/j.still.2020.104914
25. Das, T. K., Bhattacharyya, R., Sharma, A. R., Das, S., Saad, A. A., & Pathak, H. (2013). Impacts of conservation agriculture on total soil organic carbon retention potential under an irrigated agro-ecosystem of the western Indo-Gangetic Plains. *European Journal of Agronomy*, *51*, 34-42. https://doi.org/10.1016/j.eja.2013.07.003
26. Das, T. K., Nath, C. P., Das, S., Biswas, S., Bhattacharyya, R., Sudhishri, S., Raj, R., Singh, B., Kakralia, S. K., Rathi, N., Sharma, A. R., Dwivedi, B. S., Biswas, A. K., & Chaudhari, S. K. (2020). Conservation Agriculture in rice-mustard cropping system for five years: Impacts on crop productivity, profitability, water-use efficiency, and soil properties. *Field Crops Research*, *250*. https://doi.org/10.1016/j.fcr.2020.107781
27. Davis, K. F., Chiarelli, D. D., Rulli, M. C., Chhatre, A., Richter, B., Singh, D., & DeFries, R. (2018). Alternative cereals can improve water use and nutrient supply in India. *Science Advances*.
28. Devineni, N., Perveen, S., & Lall, U. (2022). Solving groundwater depletion in India while achieving food security. *Nature Communications*, *13*(1).
29. Dhanda, S., Yadav, A., Yadav, D. B., & Chauhan, B. S. (2022). Emerging Issues and Potential Opportunities in the Rice-Wheat Cropping System of North-Western India. *Front Plant Sci*, *13*, 832683. https://doi.org/10.3389/fpls.2022.832683
30. Dhillon, B. S., Kataria, P., & Dhillon, P. K. (2010). National food security vis-à-vis sustainability of agriculture in high crop productivity regions. *Current Science*, *98*.
31. EU. (1991). Directive 91/676/EEC, *European Union, Concerning the protection of waters against pollution caused by nitrates from agricultural sources*.
32. Druille, M., Garcia-Parisi, P., Golluscio, R. A., Cavagnaro, F. P., & Omacini, M. (2016). Repeated annual glyphosate applications may impair beneficial soil microorganisms in temperate grassland. *Agriculture, Ecosystems & Environment*, *230*, 184– 190.
33. Dutta, S. G., Mukherjee, A., Bhattacharya, J., & Bhattacharya, A. (2018). An Overview of Agricultural Pollutants and Organic Contaminants in Groundwater of India. In *Groundwater of South Asia* (pp. 247-255). Springer Hydrogeology.
34. Fagodiya, R. K., Singh, A., Singh, R., Rani, S., Kumar, S., Rai, A. K., Sheoran, P., Chandra, P., Yadav, R. K., Sharma, P. C., Biswas, A. K., & Chaudhari, S. K. (2023). The food-energy-water-carbon nexus of the rice-wheat production system in the western Indo-Gangetic Plain of India: An impact of irrigation system, conservational tillage and residue management. *Science of the Total Environment*, *860*, 160428. https://doi.org/10.1016/j.scitotenv.2022.160428
35. FAO. (2022). *World Food and Agriculture – Statistical Yearbook 2022. Rome.*
36. FAO. (2023). Conservation Agriculture. https://www.fao.org/conservation-agriculture/en/#:~:text=Conservation%20Agriculture%20is%20a%20farming,and%20diversification%20of%20plant%20species.
37. Fishman, R., Devineni, N., & Raman, S. (2015). Can improved agricultural water use efficiency save India's groundwater? *Environmental Research Letters*, *10*(8).
38. Fishman, R., Kishore, A., Rothler, Y., Ward, P.S., Jha, S., Singh, R.K.P. (2016). Can information Help Reduce Imbalanced Application of Fertilizers in India? Experimental Evidence from Bihar. In. International Food Policy Research Institute, New Delhi: South Asia office.
39. Fox, E., Gulledge, J., Engelhaupt, E., Burow, M. E., & McLachlan, J. A. (2007). Pesticides Reduce Symbiotic Efficiency of Nitrogen-Fixing Rhizobia and Host Plants. *Pnas,*, *104*(24).
40. Gathala, M. K., Kumar, V., Sharma, P. C., Saharawat, Y. S., Jat, H. S., Singh, M., Kumar, A., Jat, M. L., Humphreys, E., Sharma, D. K., Sharma, S., & Ladha, J. K. (2013). Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic Plains of India. *Agriculture, Ecosystems & Environment*, *177*. https://doi.org/10.1016/j.agee.2013.06.002
41. GOI. (2012): Compendium of Soil Health. In.: Department of Agriculture and Cooperation, Ministry of Agriculture, India.
42. GOI. (2018). Report of the Committee on Doubling Farmers' Income, Input Management for Resource Use Efficiency & Total Factor Productivity, *Ministry of Agriculture & Farmers' Welfare*.

43. Gora, M. K., Kumar, S., Jat, H. S., Kakraliya, S. K., Choudhary, M., Dhaka, A. K., Jat, R. D., Kakraliya, M., Sharma, P. C., & Jat, M. L. (2022). Scalable diversification options delivers sustainable and nutritious food in Indo-Gangetic plains. *Scientific Reports*, *12*(1), 14371. https://doi.org/10.1038/s41598-022-18156-1
44. Guardian, T. (2023). *India floods: monsoon rains leave 22 dead in north as Delhi sees wettest July day in decades*
45. Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., ... & Zhang, F. S. (2010). Significant acidification in major Chinese croplands. *Science*, *327*(5968), 1008-1010.
46. Handral, A. R., Singh, A., Singh, D., Suresh, A., & Jha, G. (2017). Scenario of changing dynamics in production and productivity of major cereals in India. *Indian Journal of Agricultural Sciences*, *87*, 1371-1376.
47. Hossain, M. E., Shahrukh, S., Hossain, S.A. (2022). Chemical Fertilizers and Pesticides: Impacts on Soil Degradation, Groundwater, and Human Health in Bangladesh. In V. P. Singh, Yadav, S., Yadav, K.K., Yadava, R.N (Ed.), *Environmental Degradation: Challenges and Strategies for Mitigation*. Water Science and Technology Library.
48. Huang, S. W., & Jin, J. Y. (2008). Status of heavy metals in agricultural soils as affected by different patterns of land use. *Environmental monitoring and assessment*, *139*, 317-327.
49. Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S., Singh, B., Yadav, S., & Sharmak, R. K. (2010). Halting the groundwater decline in North-West India-which crop technologies will be winners. *Advances in Agronomy*, *109*. https://doi.org/10.1016/S0065-2113(10)09005-X
50. Islam, M. R., Trivedi, P., Palaniappan, P., Reddy, M. S., & Sa, T. (2009). Evaluating the effect of fertilizer application on soil microbial community structure in rice based cropping system using fatty acid methyl esters (FAME) analysis. *World Journal of Microbiology and Biotechnology*, *25*, 1115-1117.
51. Jain, N., Sehgal, V.K., Singh, S., Kaushik, N. (2018). Estimation of Surplus Crop Residue in India for Biofuel Production. Technology Information, Forecasting and Assessment Council (TIFAC), New Delhi.
52. Jat, H. S., Datta, A., Choudhary, M., Sharma, P. C., Yadav, A. K., Choudhary, V., Gathala, M. K., Jat, M. L., & McDonald, A. (2019). Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. *Catena*, *181*.
53. Jat, H. S., Kumar, V., Datta, A., Choudhary, M., Yadvinder, S., Kakraliya, S. K., Poonia, T., McDonald, A. J., Jat, M. L., & Sharma, P. C. (2020). Designing profitable, resource use efficient and environmentally sound cereal based systems for the Western Indo-Gangetic plains. *Scientific Reports*, *10*(1), 19267. https://doi.org/10.1038/s41598-020-76035-z
54. Jat, H. S., Kumar, V., Kakraliya, S. K., Abdallah, A. M., Datta, A., Choudhary, M., Gathala, M. K., McDonald, A. J., Jat, M. L., & Sharma, P. C. (2021). Climate-smart agriculture practices influence weed density and diversity in cereal-based agri-food systems of western Indo-Gangetic plains. *Scientific Reports*, *11*(1), 15901. https://doi.org/10.1038/s41598-021-95445-1
55. Jat, M., Gathala, M., Ladha, J., Saharawat, Y., Jat, A., Kumar, V., Sharma, S., Kumar, V., & Gupta, R. (2009). Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. *Soil and Tillage Research*, *105*(1), 112-121. https://doi.org/10.1016/j.still.2009.06.003
56. Jat, M. L., Singh, B., & Gerard, B. (2014). Nutrient Management and Use Efficiency in Wheat Systems of South Asia. *Advances in Agronomy*, *125*. https://doi.org/10.1016/B978-0-12-800137-0.00005-4
57. Jat, N. K., Yadav, R. S., Kumar, S., Shamim, M., Ravisankar, N., Babu, S., & Panwar, A. S. (2018). Influence of different nutrient management practices on productivity, profitability and nutrient dynamics in basmati rice (Oryza sativa) – wheat (Triticum aestivum) cropping systems in western Indo-Gangetic Plains of India. *Indian Journal of Agricultural Sciences*.
58. Joseph, J., Scheidegger, J. M., Jackson, C. R., Barik, B., & Ghosh, S. (2022). Is flood to drip irrigation a solution to groundwater depletion in the Indo-Gangetic plain? *Environmental Research Letters*, *17*(10). https://doi.org/ARTN 10400210.1088/1748-9326/ac8f5d
59. Kahlown, M. A., Raoof, A., Zubair, M., & Kemper, W. D. (2007). Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. *Agricultural Water Management*, *87*(3), 292-298. https://doi.org/10.1016/j.agwat.2006.07.011
60. Kakraliya, S. K., Jat, H. S., Singh, I., Sapkota, T. B., Singh, L. K., Sutaliya, J. M., Sharma, P. C., Jat, R. D., Choudhary, M., Lopez-Ridaura, S., & Jat, M. L. (2018). Performance of portfolios of climate smart agriculture practices in a rice-wheat system of western Indo-Gangetic plains. *Agricultural Water Management*, *202*, 122-133. https://doi.org/10.1016/j.agwat.2018.02.020

61. Kalia, A., and Gosa, S. K. (2011). Effect of pesticide application on soil microorganisms. *Archives of Agronomy and Soil Science*, *57*(6).
62. Kassam, A. H., Friedrich, T., Derpsch, R., & Kienzle, J. (2015). Overview of the worldwide spread of conservation agriculture. *Field Actions Science Reports*, *8*.
63. Kaushik, C. P., Sharma, H. R., & Kaushik, A. (2012). Organochlorine pesticide residues in drinking water in the rural areas of Haryana, India. *Environmental monitoring and assessment*, 184, 103-112.
64. Khedwal, R. S., Chaudhary, A., Sindhu, V. K., Yadav, D. B., Kumar, N., Chhokar, R. S., Poonia, T. M., Kumar, Y., & Dahiya, S. (2023). Challenges and technological interventions in rice-wheat system for resilient food-water-energy-environment nexus in North-western Indo-Gangetic Plains: A review. *Cereal Research Communications*, 1-23. https://doi.org/10.1007/s42976-023-00355-9
65. Koutsos, T. M., Menexes, G. C., & Dordas, C. A. (2019). An efficient framework for conducting systematic literature reviews in agricultural sciences. *Science of the Total Environment*, *682*, 106-117. https://doi.org/10.1016/j.scitotenv.2019.04.354
66. Kumar, G., Ramesh, T., Subrahmaniyan, K., & Ravi, V. (2018). Effect of sprinkler irrigation levels on the performance of rice genotypes under aerobic condition. *International Journal of Current Microbiology and Applied Sciences*, *3*, 1848-1852.
67. Kumar, V. (2018). Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. *Agriculture, Ecosystems & Environment*, *252*.
68. Kumar, V., & Ladha, J. K. (2011). Direct Seeding of Rice: Recent Developments and Future Research Needs. *Advances in Agronomy*, *111*. https://doi.org/10.1016/B978-0-12-387689-8.00001-1
69. Kumari, M., & Rai, S. C. (2020). Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes using water quality index in semi arid region of India. *Journal of the Geological Society of India*, 95, 159-168.
70. Lant, C. L., Ruhl, J. B., & Kraft, S. E. (2008). The tragedy of ecosystem services. *BioScience*, 58(10), 969-974.
71. Larson, W. E., & Pierce, F. J. (1994). *The Dynamics of Soil Quality as a Measure of Sustainable Management*.
72. Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Loannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *theBMJ*. https://doi.org/10.1136/bmj.b2700
73. Lobell, D. B., Sibley, A., & Ortiz-Monasterio, J. I. (2012). Extreme heat effects on wheat senescence in India. *Nature Climate Change*, *2*(3), 186-189. https://doi.org/10.1038/Nclimate1356
74. Majumdar, K., Sanyal, S. K., Dutta, S. K., Satyanarayana, T., Singh, V. K., Singh, U., Praharaj, C., Singh, S., & Singh, N. (2016). Nutrient Mining: Addressing the Challenges to Soil Resources and Food Security. *Biofortification of Food Crops*. https://doi.org/10.1007/978-81-322-2716-8_14
75. Mandal, A., Sarkar, B., Mandal, S., Vithanage, M., Patra, A. K., & Manna, M. C. (2019). Impact of agrochemicals on soil health. In *Agrochemicals Detection, Treatment and Remediation* (pp. 161-187). https://doi.org/10.1016/B978-0-08-103017-2.00007-6
76. Mari, G. R., Ji ChangYing, J. C., & Zhou Jun, Z. J. (2008). Effects of soil compaction on soil physical properties and nitrogen, phosphorus, potassium uptake in wheat plants.
77. Martınez-Toledo, M. V., Salmeron, V., Rodelas, B., Pozo, C., & Gonzalez-Lopez, J. (1998). Effects of the fungicide Captan on some functional groups of soil microflora. *Applied Soil Ecology*, 7, 245–255. https://doi.org/10.1016/S0929-1393(97)00026-7
78. Mishra, A. K., Shinjo, H., Jat, H. S., Jat, M. L., Jat, R. K., Funakawa, S., & Sutaliya, J. M. (2022). Farmers' perspectives as determinants for adoption of conservation agriculture practices in Indo-Gangetic Plains of India. *Resources, Conservation & Recycling Advances*, *15*. https://doi.org/10.1016/j.rcradv.2022.200105
79. Modak, K., Biswas, D. R., Ghosh, A., Pramanik, P., Das, T. K., Das, S., Kumar, S., Krishnan, P., & Bhattacharyya, R. (2020). Zero tillage and residue retention impact on soil aggregation and carbon stabilization within aggregates in subtropical India. *Soil & Tillage Research*, *202*.
80. Mukherjee, A., Bhanja, S. N., & Wada, Y. (2018). Groundwater depletion causing reduction of baseflow triggering Ganges river summer drying. *Scientific Reports*. https://doi.org/10.1038/s41598-018-30246-7
81. NAAS. (2021). *Strategies for Enhancing Soil Organic Carbon for Food Security and Climate Action*.

82. Naresh, R. K., R.K. Gupta, Vivek, R.S. Rathore, S.P. Singh, Ashok Kumar, Sunil Kumar, D.K. Sachan, S.S. Tomar, N.C. Mahajan, Lali Jat and Mayank Chaudhary. (2018). Carbon, nitrogen dynamics and soil organic carbon retention potential after 18 years by different land uses and nitrogen management in rwcs under typic ustochrept soil. *International Journal of Current Microbiology and Applied Sciences*, *7*(12), 3376-3399. https://doi.org/10.20546/ijcmas.2018.712.388

83. Newman, M. M., Hoilett, N., Lorenz, N., Dick, R. P., Liles, M. R., Ramsier, C., et al. . (2016). Glyphosate effects on soil rhizosphere-associated bacterial communities. *Science of the Total Environment*, *543*, 155–160.

84. Oerke, E. C. (2006). Crop losses to pests: centenary review. *Journal of Agricultural Science*, *144*, 31-43. https://doi.org/10.1017/S0021859605005708

85. Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., Kamili, A.N. . (2021). Chemical Fertilizers and Their Impact on Soil Health. In G. H. Dar, Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (Ed.), *Microbiota and Biofertilizers* (Vol. 2). Springer. https://doi.org/10.1007/978-3-030-61010-4_1

86. Pant, D., Keesari, T., Rishi, M., Jaryal, A., Sharma, D. A., Thakur, N., Singh, G., Kamble, S. N., Sangwan, P., Sinha, U. K., & Tripathi, R. M. (2020). Quality and quantity of groundwater in highly exploited aquifers of Northwest India. *Journal of hazardous, toxic, and radioactive waste*, 24(2).

87. Parihar, C. M., Jat, S. L., Singh, A. K., Ghosh, A., Rathore, N. S., Kumar, B., Pradhan, S., Majumdar, K., Satyanarayana, T., Jat, M. L., Saharawat, Y. S., Kuri, B. R., & Saveipune, D. (2017). Effects of precision conservation agriculture in a maize-wheat-mungbean rotation on crop yield, water-use and radiation conversion under a semiarid agro-ecosystem. *Agricultural Water Management*, *192*, 306-319. https://doi.org/10.1016/j.agwat.2017.07.021

88. Parihar, C. M., Singh, A. K., Jat, S. L., Dey, A., Nayak, H. S., Mandal, B. N., Saharawat, Y. S., Jat, M. L., & Yadav, O. P. (2020). Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. *Soil and Tillage Research*, *202*. https://doi.org/10.1016/j.still.2020.104653

89. Pathak, H., 2010. . (2010). Trend of fertility status of Indian soils. *Current Advances in Agricultural Sciences*, 2(1), 10-12.

90. Prashar, P., Shah, S. (2016). Impact of Fertilizers and Pesticides on Soil Microflora in Agriculture. In E. Lichtfouse (Ed.), S*ustainable Agriculture Reviews*, 19. Springer. https://doi.org/10.1007/978-3-319-26777-7_8

91. Rahman, K. M., & Zhang, D. . (2018). Effects of Fertilizer Broadcasting on the Excessive Use of Inorganic Fertilizers and Environmental Sustainability. *sustainability*, *10*(3), 759. https://doi.org/10.3390/su10030759

92. Raj, R., Das, T. K., Pankaj, Banerjee, T., Ghosh, A., Bhattacharyya, R., Chakraborty, D., Prasad, S., Babu, S., Kumar, V., Sen, S., & Ghosh, S. (2022). Co-implementation of conservation tillage and herbicides reduces weed and nematode infestation and enhances the productivity of direct-seeded rice in North-western Indo-Gangetic Plains. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.1017013

93. Rana, B., Parihar, C. M., Nayak, H. S., Patra, K., Singh, V. K., Singh, D. K., Pandey, R., Abdallah, A., Gupta, N., Sidhu, H. S., Gerard, B., & Jat, M. L. (2022). Water budgeting in conservation agriculture-based sub-surface drip irrigation using HYDRUS-2D in rice under annual rotation with wheat in Western Indo-Gangetic Plains. *Field Crops Research*, *282*. https://doi.org/10.1016/j.fcr.2022.108519

94. Rashid, M. H., Alam, M. M., Khan, M. A. H., & Ladha, J. K. (2009). Productivity and resource use of direct-(drum)-seeded and transplanted rice in puddled soils in rice–rice and rice–wheat ecosystems. *Field Crops Research*, *113*(3). https://doi.org/10.1016/j.fcr.2009.06.004

95. Rautaray, S. K., & Sucharita, S. (2024). Crop diversification for a sustainable agriculture. *Indian Farming*, 74(2), 19-22.

96. Rickman, J. F. (2002). *Manual for Laser Land Leveling. Rice–Wheat Consortium Technical Bulletin Series 5* Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India.

97. Russo, T. A., Devineni, N., Lall, U. . (2015). Assessment of Agricultural Water Management in Punjab, India, Using Bayesian Methods. 147–162. https://doi.org/10.1007/978-3-319-12194-9_9

98. Saha, D., & Alam, F. (2014). Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. *Environmental Monitoring and Assessment*, *186*(12), 8741-8763. https://doi.org/10.1007/s10661-014-4041-x

99. Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M. K., Jat, M. L., & Kumar, V. (2010). Evaluation of alternative tillage and crop establishment methods in a rice–wheat rotation in North Western IGP. *Field Crops Research*.

100. Saikia, R., Sharma, S., Thind, H., & Sidhu, H. . (2019). Temporal changes in biochemical indicators of soil quality in response to tillage, crop residue and green manure management in a rice-wheat system. *Ecological Indicators*, *103*, 383-394. https://doi.org/10.1016/j.ecolind.2019.04.035
101. Sandhu, O. S., Gupta, R. K., Thind, H. S., Jat, M. L., Sidhu, H. S., & Yadvinder, S. (2019). Drip irrigation and nitrogen management for improving crop yields, nitrogen use efficiency and water productivity of maize-wheat system on permanent beds in north-west India. *Agricultural Water Management*, *219*, 19-26. https://doi.org/10.1016/j.agwat.2019.03.040
102. Sapkota, T. B., Jat, R. K., Singh, R. G., Jat, M. L., Stirling, C. M., & Jat, M. K. (2017). Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. *Soil Use Management*, *33*. https://doi.org/10.1111/sum.12331
103. Savci, S. (2012). An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development*, *3*(1), 73.
104. Scott, C. A., & Sharma, B. (2009). Energy supply and the expansion of groundwater irrigation in the Indus-Ganges Basin, *International Journal of River Basin Management*. *7*(2). https://doi.org/10.1080/15715124.2009.9635374
105. Shah, S. S., Mathur, S. & Chakma, S. (2023). Numerical modeling of one-dimensional variably saturated flow in a homogeneous and layered soil–water system via mixed form Richards equation with Picard iterative scheme. *Modeling Earth Systems and Environment*, *9*(2027–2037). https://doi.org/10.1007/s40808-022-01588-z
106. Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, *4*, 035005. https://doi.org/10.1088/1748-9326/4/3/035005
107. Shahzad, M., Farooq, M., & Hussain, M. (2016). Weed spectrum in different wheat-based cropping systems under conservation and conventional tillage practices in Punjab, Pakistan. *Soil & Tillage Research*. https://doi.org/10.1016/j.still.2016.05.012
108. Sharda, R., Mahajan, G., & Siag, M. (2017). Performance of drip-irrigated dry-seeded rice (Oryza sativa L.) in South Asia. *Paddy and Water Environment*, *15*. https://doi.org/10.1007/s10333-016-0531-5
109. Sharda, V., Kurothe, R., Sena, D., Pande, V., & Tiwari, S. (2006). Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. *Journal of Hydrology*, *329*(1-2), 224-243. https://doi.org/10.1016/j.jhydrol.2006.02.015
110. Sharma, P. C., Datta, A., Yadav, A. K., Choudhary, M., Jat, H. S., & McDonald, A. (2018). Effect of Crop Management Practices on Crop Growth, Productivity and Profitability of Rice–Wheat System in Western Indo-Gangetic Plains. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, *89*(2), 715-727. https://doi.org/10.1007/s40011-018-0985-x
111. Sharma, S., Singh, P., Choudhary, O. P., & Neemisha. (2021). Nitrogen and rice straw incorporation impact nitrogen use efficiency, soil nitrogen pools and enzyme activity in rice-wheat system in north-western India. *Field Crops Research*, *266*. https://doi.org/10.1016/j.fcr.2021.108131
112. Sharma, V. K., Ladha, J. K., & Bhushan, L. (2003). Soil Physical Effects of Puddling in Rice-Wheat Cropping Systems. Improving the Productivity and Sustainability of Rice- Wheat Systems: Issues and Impacts. *ASA Special publication*, *65*.
113. Shekhar, S., Kumar, S., Densmore, A. L., van Dijk, W. M., Sinha, R., Kumar, M., Joshi, S. K., Rai, S. P., & Kumar, D. (2020). Modelling water levels of northwestern India in response to improved irrigation use efficiency. *Scientific Reports*, *10*(1), 13452. https://doi.org/10.1038/s41598-020-70416-0
114. Shivay, Y. S., Pooniya, V., Pal, M., Ghasal, P. C., Bana, R., & Jat, S. L. (2019). Coated Urea Materials for Improving Yields, Profitability, and Nutrient Use Efficiencies of Aromatic Rice. *Global Challenges*, *3*(12), 1900013. https://doi.org/10.1002/gch2.201900013
115. Sidhu, H. S., Jat, M. L., Singh, Y., Sidhu, R. K., Gupta, N., Singh, P., Singh, P., Jat, H. S., & Gerard, B. (2019). Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: A breakthrough for addressing water and nitrogen use efficiency. *Agricultural Water Management*, *26*. https://doi.org/10.1016/j.agwat.2019.02.019
116. Singh, A., Phogat, V., Dahiya, R., & Batra, S. (2014). Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice–wheat cropping system. *Soil and Tillage Research*, *140*, 98-105. https://doi.org/10.1016/j.still.2014.03.002
117. Singh, B., Humphreys, E., Gaydon, D. S., & Eberbach, P. L. (2016). Evaluation of the effects of mulch on optimum sowing date and irrigation management of zero till wheat in central Punjab, India using APSIM. *Field Crops Research*, *197*, 83-96.

https://doi.org/10.1016/j.fcr.2016.08.016

118. Singh, B., & Singh, V. P. (2012). Productivity and fertility of soils in the Indo-Gangetic Plains of South Asia. *Archives of Agronomy and Soil Science, 58*. https://doi.org/10.1080/03650340.2012.693600
119. Singh, K. P., Malik, A., Mohan, D., & Sinha, S. (2005). Persistent organochlorine pesticide residues in alluvial groundwater aquifers of Gangetic Plains, India. *Bulletin of Environmental Contamination and Toxicology*, 74(1), 162-169.
120. Singh, O., Kasana, A., & Bhardwaj, P. (2022a). Understanding energy and groundwater irrigation nexus for sustainability over a highly irrigated ecosystem of north western India. *Applied Water Science*. https://doi.org/10.1007/s13201-021-01543-w
121. Singh, R., Singh, A., Sheoran, P., Fagodiya, R. K., Rai, A. K., Chandra, P., Rani, S., Yadav, R. K., & Sharma, P. C. (2022b). Energy efficiency and carbon footprints of rice-wheat system under long-term tillage and residue management practices in western Indo-Gangetic Plains in India. *Energy*, *244*. https://doi.org/10.1016/j.energy.2021.122655
122. Singh, R., Yadav, D. B., Yadav, A., & Punia, S. S. (2021). Characterization of herbicide use and factors responsible for herbicide resistance in Phalaris minor in wheat in Haryana, India. *Crop Protection*, *144*. https://doi.org/10.1016/j.cropro.2021.105581
123. Singh, V. K., Dwivedi, B. S., Buresh, R. J., Jat, M. L., Majumdar, K., Gangwar, B., Govil, V., & Singh, S. K. (2013). Potassium Fertilization in Rice–Wheat System across Northern India: Crop Performance and Soil Nutrients. *Agronomy Journal*, *105*(2).
124. Singh, Y., & Sidhu, H. S. (2014). Management of Cereal Crop Residues for Sustainable Rice-wheat Production System in the Indo-gangetic Plains of India. *Proceedings of the Indian National Science Academy*, *80*(1). https://doi.org/10.16943/ptinsa/2014/v80i1/55089
125. Singh, Y., & Singh, B. (2008). Efficient Management of Primary Nutrients in the Rice-Wheat System. *Journal of Crop Production*, *4*(1), 23-85. https://doi.org/10.1300/J144v04n01_02
126. Sishodia, R. P., Shukla, S., Wani, S. P., Graham, W. D., & Jones, J. W. . (2018). Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India. *Science of the Total Environment*, *635*(725-740). https://doi.org/10.1016/j.scitotenv.2018.04.130
127. Soman, P., Prasad, M. S., Balasubramaniam, V. R., Sarwan Singh, Dhavarajan, C., Patil, V. B., & Sanjeev Jha. . (2018). Effect of drip irrigation and fertigation on the performance of several rice cultivars in different rice ecosystems in India. *International Journal of Agriculture Sciences*, *10*(14), 6672-6675.
128. Soni, J. K., Nibhoria, A., Punia, S. S., Yadav, D. B., Choudhary, V. K., Lalramhlimi, B., & Navik, O. (2023). Herbicide resistant Phalaris minor in India—history of evolution, present status and its management. *Phytoparasitica*. https://doi.org/10.1007/s12600-022-01039-6
129. Srivastava, S. K., Chand, R., & Singh, J. (2017). Changing crop production cost in India: Input prices, substitution and technological effects, *Agricultural Economics Research Review*.
130. Stuart, M. E., Gooddy, D. C., Bloomfield, J. P., & Williams, A. T. (2011). A review of the impact of climate change on future nitrate concentrations in groundwater of the UK. *Science of the Total Environment*, 409(15), 2859-2873.
131. Surendran, U., Raja, P., Jayakumar, M., & Subramoniam, S. R. (2021). Use of efficient water saving techniques for production of rice in India under climate change scenario: A critical review. *Journal of Cleaner Production*, *309*.
132. Thind, H. S., Sharma, S., Sidhu, H. S., Singh, V., & Singh, Y. (2023). Tillage, crop establishment and residue retention methods for optimising productivity and profitability under rice–wheat system. *Crop and Pasture Science*. https://doi.org/10.1071/cp21595
133. Thind, H. S., Singh, Y., Sharma, S., Goyal, D., Singh, V., & Singh, B. (2017). Optimal rate and schedule of nitrogen fertilizer application for enhanced yield and nitrogen use efficiency in dry-seeded rice in north-western India. *Archives of Agronomy and Soil Science*, *64*(2), 196-207. https://doi.org/10.1080/03650340.2017.1340642
134. UN. (2022). Department of Economic and Social Affairs, World Population Prospects United Nations. https://population.un.org/wpp/
135. Vera, S., Hans, G. J. M., Paul, Z., Marc, T., Ritsema, C. J., & Geissen, V. (2019). Pesticide residues in European agricultural soils – A hidden reality unfolded. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2018.10.441
136. Verma, A., Sharma, A., Kumar, R., & Sharma, P. . (2023). Nitrate contamination in groundwater and associated health risk assessment for Indo-Gangetic Plain, India. *Groundwater for Sustainable Development*, *23*. https://doi.org/10.1016/j.gsd.2023.100978

137. Verma, A. K., & Dewangan, M. L. (2006). Efficiency and energy use in puddling of lowland rice grown on Vertisols in Central India. *Soil and Tillage Research*, *90*. https://doi.org/10.1016/j.still.2005.08.009
138. Weisberger, D., Nichols, V., & Liebman, M. (2019). Does diversifying crop rotations suppress weeds? A meta-analysis. *PLoS One*, *14*.
139. White, J. W., & Rodriguez, A. (2008). An Agroclimatological Characterization of the Indo-Gangetic Plains. *Journal of Crop Production*, *3*(2), 53-65. https://doi.org/10.1300/J144v03n02_03
140. Wu, C., Wang, Z., Ma, Y., Luo, J., Gao, X., Ning, J., Mei, X., & She, D. (2021). Influence of the neonicotinoid insecticide thiamethoxam on soil bacterial community composition and metabolic function. *Journal of Hazardous Materials*, *405*. https://doi.org/10.1016/j.jhazmat.2020.124275
141. Yadav, D. B., Yadav, A., Punia, S. S., and Chauhan, B. S. (2016). Management of herbicide-resistant Phalaris minor in wheat by sequential or tank-mix applications of pre- and post-emergence herbicides in north-western IndoGangetic Plains. *Crop Protection*, *89*(239–247).
142. Yadav, M. R., Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, D., Pooniya, V., Parihar, M. D., Saveipune, D., Parmar, H., & Jat, H. S. (2015). Effect of Long-Term Tillage Practices and Diversified Crop Rotations on Nutrient Uptake, Profitability and Energetics of Maize. *Indian Journal of Agricultural Sciences*.
143. Yadav, R. L., Singh, S. R., Prasad, K., Dwivedi, B. S., Batta, R. K., Singh, A. K., Patil, N. G., & Chaudhary, S. K. (2000). Management of irrigated ecosystem. In *National Resource Management for Agricultural Production in India*, 775–870.
144. Yang, Z. H., Ping, L. S., Ping, S. X., Qing, C. H., & Fei, L. J. (1999). Effect of long term minimum and zero-tillage on rice and wheat yield, organic matter and bulk density. *Scientia Agriculture Sinica*, *34*, 39-44.
145. Yardirn, E. N., & Edwards, C. A. (1998). The effects of chemical pest, disease and weed management practices on the trophic structure of nematode populations in tomato agroecosystems. *Applied Soil Ecology*, *7*, 137–147. https://doi.org/10.1016/S0929-1393(97)00036-X.
146. Yasmin, S., & D’Souza, D. (2010). Effects of pesticides on the growth and reproduction of earthworm: A review. *Applied and Environmental Soil Science*, *3*, 1-9.
147. Zhang, J., Bo, G., Zhang, Z., Kong, F., Wang, Y., and Shen, G. (2016). Effects of straw incorporation on soil nutrients, enzymes, and aggregate stability in tobacco fields of China. *sustainability*, *8*(710- 721).

Footnotes

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.
2. Based on the Scopus and Web of Science using broad terms such as " Pesticide, AND Gangetic Plain (includes Indo-Gangetic Plain, Northwestern Gangetic Plain).

Figures

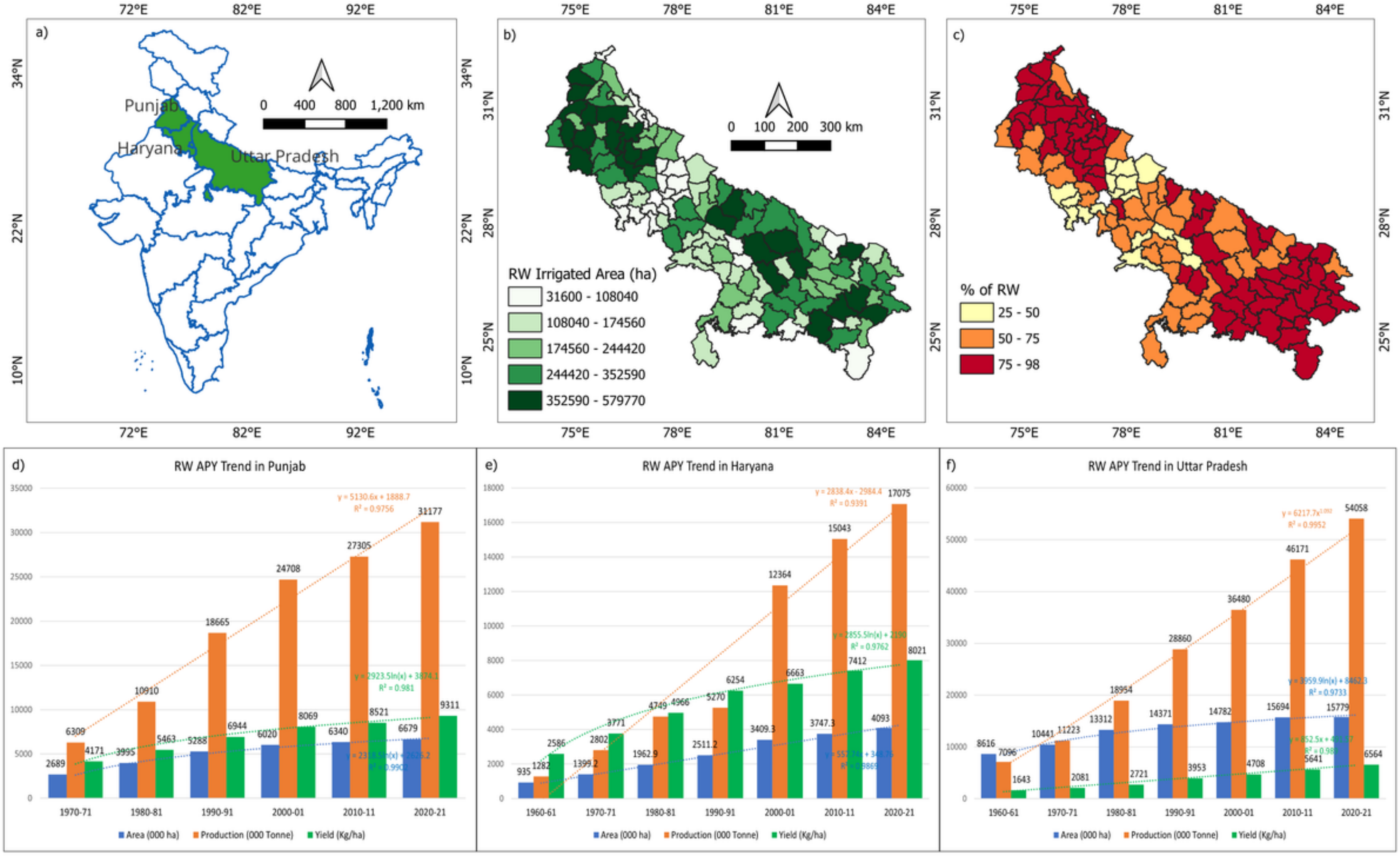

Figure 1

Trend of area, production, and yield in rice-wheat (RW) system (a, NW IGP 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)

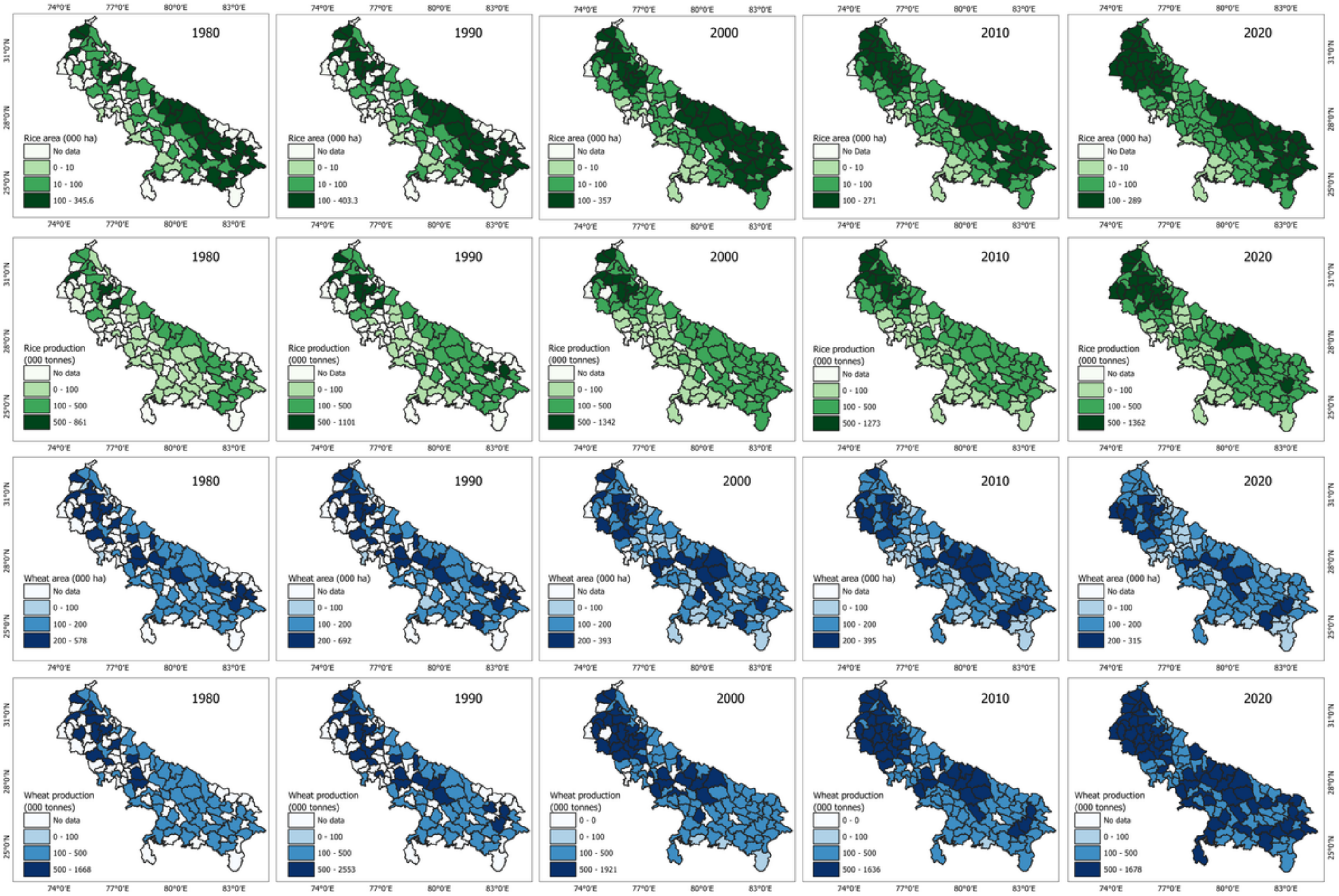

Figure 2

District-wise area and production in NW IGP (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.

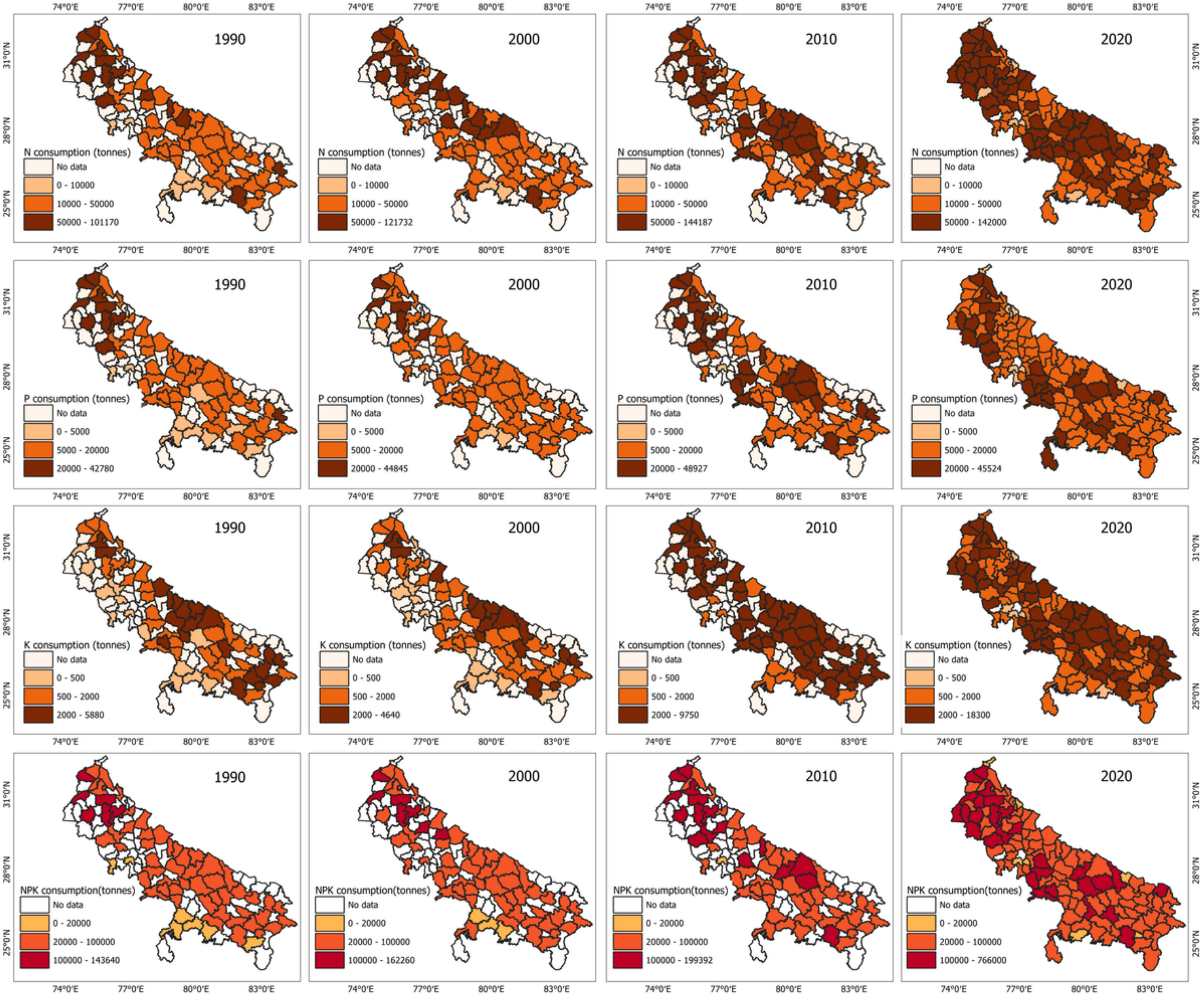

Figure 3

District-wise fertilizer consumption in NW IGP from 1990-2020 (Top 1st row, Nitrogen(N) consumption in tonnes, Top 2nd row, Phosphorous(P) consumption in tonnes, Top 3rd row, Potassium(K) consumption in tonnes, Last row, NPK consumption in tonnes. Source: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

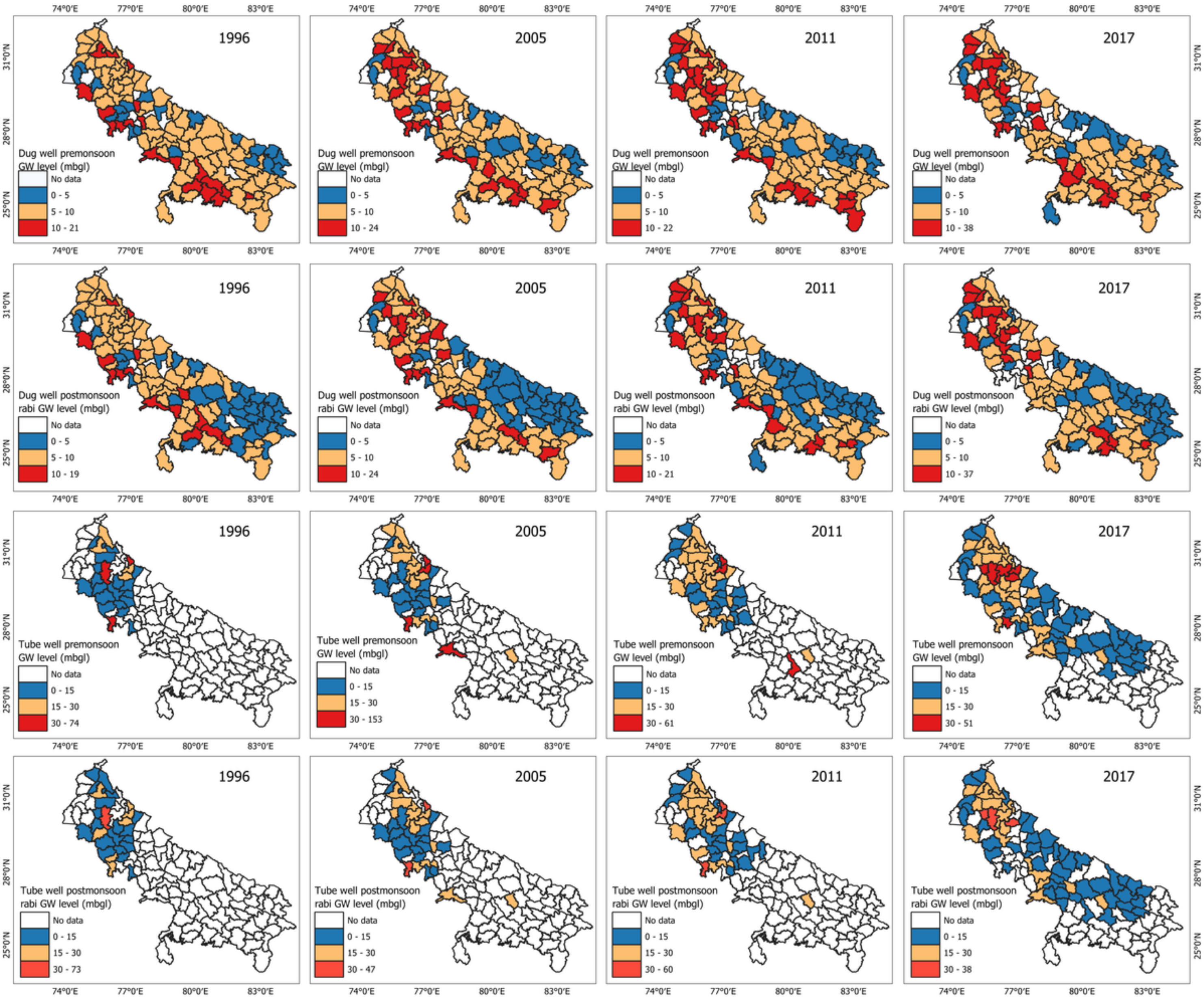

Figure 4

District-wise groundwater levels in NW IGP 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)

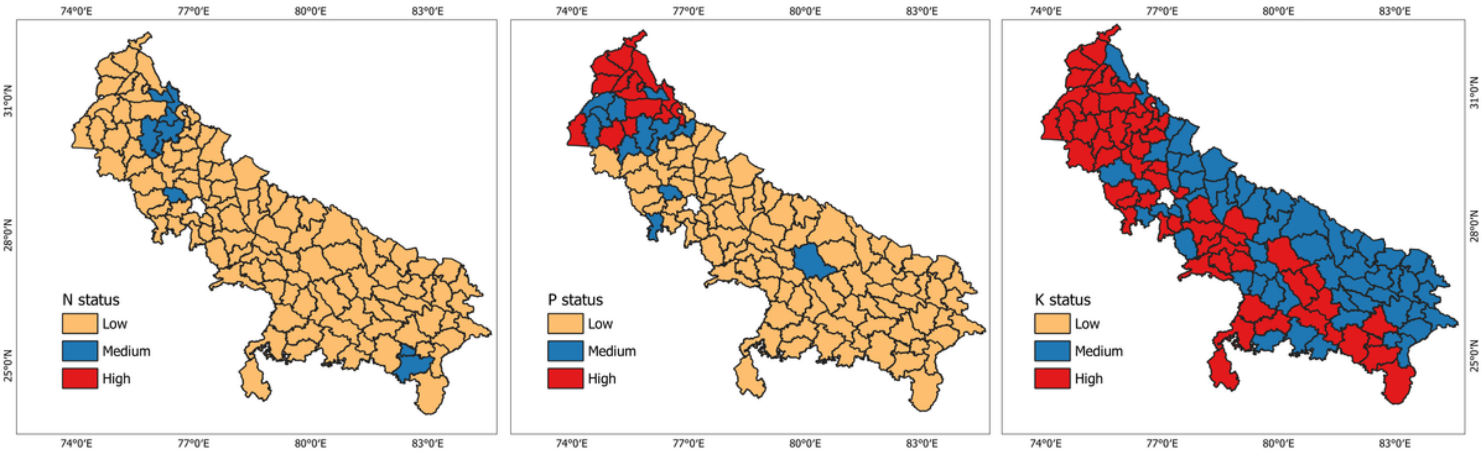

Figure 5

District-level soil fertility status of NW IGP districts. (N=Nitrogen, P=Phosphorus and K=Potassium). Source: Compendium on Soil Health (GOI, 2012).

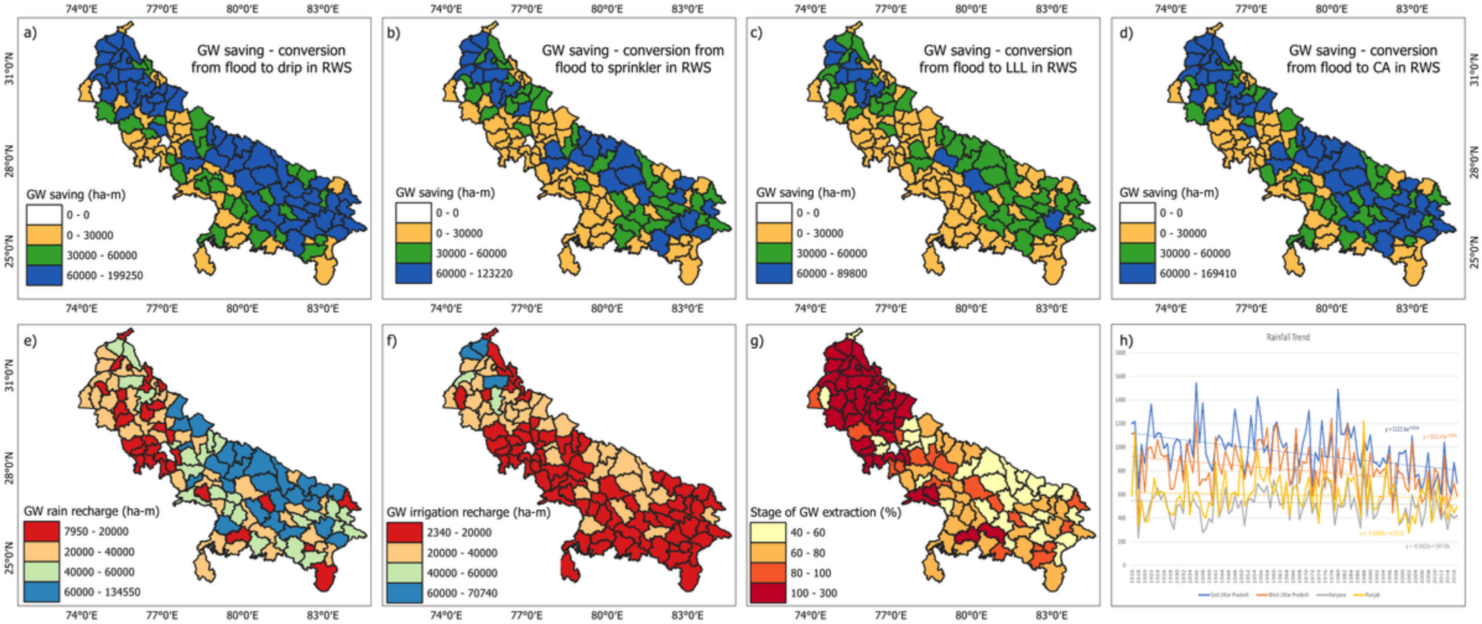

Figure 6

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. e, stage of GW extraction. h, trend of 100 years annual rainfall in Punjab, Haryana, Western and Eastern Uttara Pradesh (1916-2016)

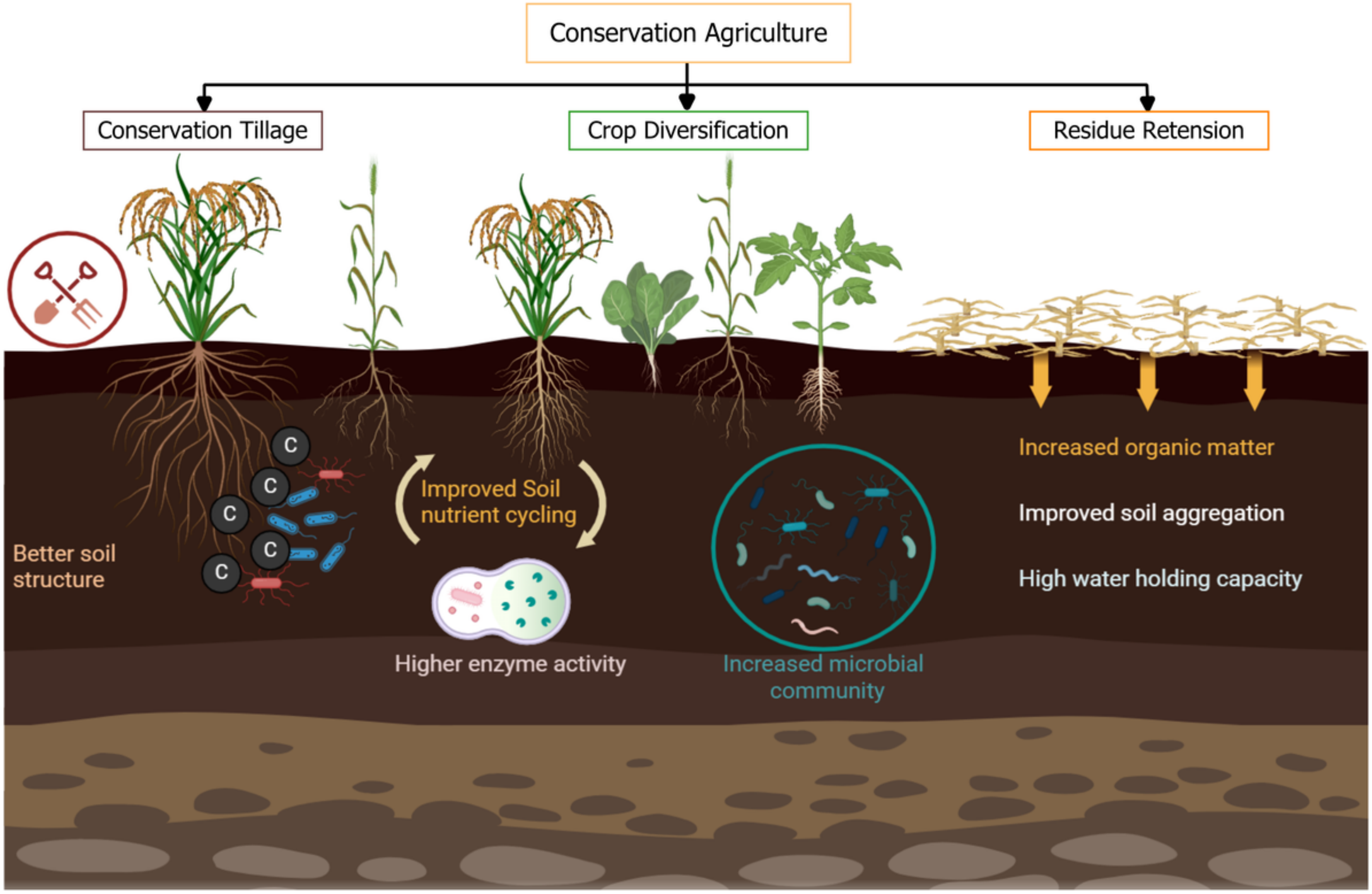

Figure 7

Effect of conservation agriculture on soil health (created with BioRender.com)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx