ADAPTATION OF TECHNOLOGICAL APPROACHES THROUGH CONSERVATION AGRICULTURE FOR SUSTAINING SOIL FERTILITY AND PRODUCTIVITY UNDER BUNDELKHAND REGION: A HOLISTIC REVIEW

Amar Singh Gaur, Deepak Prajapati, Suraj Mishra, K.M. Tripathi and Jagannath Pathak
Department of Soil Science and Agricultural Chemistry
Banda University of Agriculture and Technology, Banda (U. P.) 210001

Introduction

History repeats itself. old day Farmar crops are cultivated in conventional methods and used of tools and practices such as ploughing to bull and crop residue management to maintain the proper soil disturbance and soil restore carbon itself which sustains the soil physical, chemical and biological properties. Recently, conventional input-intensive agriculture has encountered limitations in the efficient utilization of natural and man–made resource bases, leading to a decline in factor productivity. Extensive soil pulverization through discing/ ploughing, harrowing, rotavation etc. In the last 2 decades, rising production costs due to price hikes in energy resources (diesel, electricity), labour and other inputs are making the CT system economically less productive/ feasible (Parihar *et al.*, 2016; Pradhan et al., 2018). If we see that environmental quality and ecosystem sustainability concerns including soil erosion and quality deterioration, high global warming potential and chemical pollution to environment, farmers, and consumers have compelled scientists/ researchers to look back to the past towards developing cost effective and resource efficient crop production technologies. Conservation Agriculture (CA) is a concept for resource saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment (FAO, 2017). Conservation agriculture is being widely endorsed by various national and international organizations/agencies for mitigating multiple challenges of groundwater depletion, inefficient resource use, climate change, and abiotic/biotic stress in crops. Adoption of CA is gradually increasing in the tropics, sub–tropics, temperate arid regions of the world, both under rainfed and irrigated ecologies. The CA is also hailed as a panacea for restoration of yield and farm income in degraded agro–ecologies in arid and semi–arid tropics (Jat *et al.,* 2012). Widely reported problems associated with the conventional puddled transplanted rice (PTR) conventional till wheat (CTW) system in north India include diminishing net income, increasing commodity costs, labour scarcity, declining water resources, soil salinity and sodicity, surface and subsurface compaction, degraded soil structure (lower hydraulic conductivity, macroporosity and water stable aggregates), weed resistance and higher greenhouse gas (GHG) emissions (Sudhir–Yadav *et al.*, 2011; Gathala *et al.*, 2013). Conservation Agriculture– based practices like dry direct seeded rice (DSR), zero–till wheat (ZTW), residue retention, crop diversification have been advocated in the RWCS of the Indo Gangetic Plains (IGP) to resolve these problems (Das *et al.,* 2014, 2016, 2020). Conservation agriculture can reverse the soil degradation processes and improve soil fertility through increased water holding capacity, reduced runoff, higher infiltration of rainwater and groundwater storage, soil organic carbon (SOC) enrichment, enhanced microbial diversity in rhizosphere and improved soil nutrient cycling (Gathala *et al*., 2011; Das *et al*., 2017, 2018a; Das *et al.,* 2020). Residues left on the fields (after mechanical harvesting) create disposal issues due to straw length/cutting height, poor nutritional quality of rice straw, cost for residue collection and transportation, and the lack of appropriate in–situ residue management technology (Singh and Sidhu, 2014). This provokes extensive burning of rice residue that causes toxic smog (suspended particulate matter; SPM) in the neighboring states, pollution and health issues, which are the prime concerns now–a–days. However, availability of advanced (residue load–specific and scale appropriate) ZT seeding machines (happy seeder, turbo seeder), combine harvesters with straw management system (SMS), low dose high potency post–emergence herbicides and favorable policy support are few important developments that could encourage farmers towards adoption of CA.

The CA or Zero till method sowing at proper time allows sufficient growth and development of a crop to obtain a satisfactory yield and also provide variable environmental conditions within the same location for growth and development of crop and yield stability (Pandey *et al.,* 1981). Hence, the present investigation on "Adaptation of technological approaches to sustain soil fertility and productivity of mustard under Bundelkhand" was undertaken to generate the scientific information on feasibility of zero till as well as the comparison effect of zero till and conventional on yield of Indian mustard. The early crop establishment through new technique could be a better alternative to minimize the yield losses in crop. The main aim of this study was to quantify the effect of direct seeding over conventional method to see the yield effect in mustard. Therefore, to address the above issues, a field experiment was conducted at student research farm Banda University of Agriculture and Technology Banda.

The Scenario

Crop failure is a common feature, either due to inadequacy of late sowing or principal practises, insufficient resource use efficiency and high temperature, a lack of soil moisture to meet crop water requirements or due to late harvest of kharif crop and proper management during different cropping systems.

Conservation Agriculture Principles and Practices

Conservation agriculture (CA) as a concept evolved in response to concerns awareness about sustainable agriculture. It enables resource and energy–efficient agricultural crop production using integrated management of agro– ecosystem (Jat *et al.,* 2020). Its aim is to achieve production intensification and high yields while maintaining/ augmenting natural resource bases through compliance with 3 inter related principles such as reduced tillage, permanent soil cover with using residue mulch or continuous cover crops, and rational diversified crop rotations usually including a legume along and legumes under cereal systems, real time nitrogen management using leaf colour chart, SPAD meter, Green Seeker, and climate smart weed management (Parihar *et al*., 2020a).

Conservation Agriculture Across the Globe

The CA has been spreading steadily in the world, covering about 180.4 million ha (~12.5%) of the world's arable land (Kassam *et al*., 2019). The share of CA area in the continents of South America, North America, Australia and New Zealand, and Asia are 38.7, 35, 12.6 and 7.7%, respectively, while meager in Europe and Africa. The CA is adopted in 78 countries of the world (till 2015–16). The USA, Brazil, Argentina, Australia, Canada, China are the leading countries promoting CA. Since 2009, adoption of CA has increased at almost 10 million ha per year in which Nepal, and Pakistan, about 13.5 million ha area is under rice and wheat crops, providing food security and livelihoods to millions of people (Timsina and Connor, 2001). Due to persistent efforts of the Rice–Wheat Consortium (RWC) and several institutions of the National Agricultural Research System (NARS), zero tillage (ZT) technology was introduced in India and the neighbouring countries, and is being gradually adopted by the farmers in IGP (Sharma, 2021). In the world, CA has spread mostly in rainfed areas, while in India, its spread is confined mostly in the irrigated belts of IGP. In India, about 1.5 million ha area is under CA, but the area under ZT in the IGP has increased steadily, reassigned to be at about 2.5 million ha (Bijarniya *et al*., 2020).

Impacts of Conservation Agricultrue on Productivity and Economics

Crop and cropping system productivity Numerous studies have revealed that, CA practices when implemented together could provide multiple benefits including increased crop performance and farm income across cropping systems and environments in India (Das *et al*., 2014, 2016, 2018, 2020; Baghel *et al*., 2018, 2020; Ghosh *et al*., 2020). Several factors like crops, location, climate, soil, duration of CA adoption, and management practices play key roles for the success of CA. Integration of CA with the best management practices (BMPs), i.e. appropriate choice of cultivar, timely sowing, proper seed rate, sowing technique and seed treatment, appropriate nutrient, weed, water and pest management improved the yields of wheat and rice by 46– 54 % and 10–24%, respectively, over CT, thereby obtaining 53% higher system yield (Laik *et al.,* 2014). Wang *et al.* (2014) from a 12 year study (1999–2011) found that, implementing ZT with subsoiling and straw cover in spring maize (Zea, mays L.) could not make any yield difference with the conventional tillage and straw removal (CTSR) in the first 3 years but had significant yield improvement over CTSR in the remaining years owing to reduced salinity stress and better soil health. Similarly, a 6–year–long CA practice in fine loamy soils involving ZT and residue retention observed a yield increment of 14.3% over conventional tillage (CT) practice in rice/ maize–wheat–mung bean [Vigna radiate (L.) R. Wilczek] cropping systems in Haryana (India), a semi–arid region of north–western Indo–Gangetic Plains (Jat *et al.,* 2019 , Yadav *et al.* 2021). (Pooniya *et al.* 2021) reported 27% higher maize grain yield under site specific nutrient management through Nutrient Expert under ZT and permanent bed over farmer's fertilizer practice. Under rainfed ecologies of eastern and south African countries, CA reduced the yield variability by 11% over CT (Nyagumbo *et al.* 2020). The highest returns (90–95%) from CA investments by small–holder farmers were realized under low– rainfall conditions (< 700 mm), thereby providing clear evidence of the climate smartness of CA systems under soil moisture–stressed conditions.

Farm Income/ Profitability

The major factor leading to lower costs in CA–based system is attributed to bypassing of preparatory tillage operations unlike CT where 4–5 primary and secondary tillage operations are performed for seedbed preparation, which incur greater costs (Erenstein and Laxmi, 2008; Jat *et al*., 2014). As per estimates, tillage and crop establishment costs could be as low as 79–95% under ZT system compared to CT system (Gathala *et al.,* 2011). Moreover, lower labour requirements, savings in fuel/diesel and inputs may also lead to the lower production costs in CA (Gathala *et al*., 2015). Baghel *et al*. (2020) observed that, despite 0.4–1.8% lower rice grain yield, CA–based ZT rice with wheat residue and effective herbicides managed to produce 164–233% higher net returns under rice–wheat system in the north–western IGP. Susha *et al*. (2018) reported 33% higher net returns under ZT– based wheat over CT in maize–wheat system in IGP. Pooniya *et al.* (2021a) observed that, CT was costlier than permanent narrow bed and ZT flat bed by 18.7 and 19.3%, respectively, while recommended dose of fertilizer (RDF) was more expensive than site specific nutrient management in maize–Indian mustard system. Economic benefits of the CA practices over CT under different crops/ cropping systems in India are shown.

Impacts of Conservation Agriculture on Resource–Use Efficiency

Water productivity and use efficiency

Conservation agriculture could be a forward-facing strategy to increase water and nutrient use efficiencies in crops and cropping systems. The ZT saved irrigation water to an extent of 20–35% in the wheat crop contrasted with CT which diminished water use by around 10 cm ha^{-1} Ghosh *et al*. (2020) observed that, DSR + mungbean residue under CA based rice– wheat–mungbean system resulted in 42% higher irrigation water–use efficiency (0.57 kg/m3) compared to PTR (0.33 kg/m3). In wheat, straw mulching increased the water use efficiency (WUE) by 14.7–34.2% over no–mulch treatment across different irrigation levels (Ram *et al*., 2013). Similarly, in a CA–based maize–wheat system, Das *et al*. (2018) observed that the plots under ZT permanent broad bed with residue could reduce 2–year mean irrigation water use by 14% (~130 mm ha^{-1}), and increase 2–year mean water productivity of maize crop by 57% over CT. Likewise, Parihar *et al.* (2016) reported that in maize, water productivity increased by 13–28% and 7–30%, under permanent beds and ZT, respectively compared to CT.

Nutrient accumulation, cycling and use efficiency

Conservation practices like permanent beds or zero till with residue retention leads to savings in soil moisture, resulting in improved soil nutrient availability and increased uptake by crop, thereby higher agronomic nutrient use efficiency and apparent nutrient recovery efficiency in crops (Nath *et al*., 2017b; Parihar *et al*., 2020a). Besides, the build–up of soil organic matter (SOM) under long term CA is expected to reduce the requirement for synthetic fertilizer over time (Yadvinder–Singh *et al*., 2015). The placement of fertilizer in bands below the residue enriched surface of ZT+R soils would reduce volatilization and nutrient immobilization. In a long–term ZT rice–wheat–mungbean system with residue retention, lowering the recommended N dose in rice and wheat (75% recommended N) led to 22% increase in partial factor productivity of N over CT rice–wheat system (Ghosh et al., 2020).

Energy productivity and use efficiency

The energy requirement of conventional mechanized agriculture is higher than CA mainly due to multiple tillage operations which consume higher fossil fuel energy (Saad *et al.,* 2016). Erenstein *et al*. (2008) in a field survey reported that, ZT restricts land preparation and crop establishment to a single pass, signifying a per hectare saving of 6–7 tractor hours and 35–36 L diesel over CT. Erenstein and Laxmi (2008) found seasonal diesel savings with zero tillage in the range of 15–60 L ha^{-1}, with an average of 36 L ha^{-1} (81% over CT). Likewise, Sangar et al. (2005) reported that ZT could save 50–60 L ha^{-1} fuel amount to ~3,000 MJ energy ha^{-1}. In maize–wheat–mungbean cropping system, Saad *et al*. (2016) observed that ZT–raised bed planting saved 91% energy in land preparation and 38%

energy in irrigation, resulting in 8% lower total energy requirement than that of CT flatbed planting. In a 7 year long CA based irrigated intensive maize system, CA practices reduced the energy consumption by 49.7–51.5% in land preparation and 16.8–22.9% in irrigation, resulting in 14.8–18.9% higher net energy returns than CT (Parihar *et al*., 2020a). Chaudhary *et al.* (2017) reported significantly higher (~50%) total energy input was in PTR over DSR due to higher energy use for nursery raising, land preparation and irrigation. Singh et al. (2016) observed that CA with suitable agricultural machinery had invariably higher energy productivity (~0.22–0.25 kg/MJ) than CT (~0.17–0.20 kg/MJ), across different crops in the states of Punjab, Haryana, Uttar Pradesh, and Madhya Pradesh.

Weed dynamics, interference, and control efficiency

Weeds pose a formidable challenge in the initial years of adoption of CA. The reduced tillage intensity in CA minimizes the opportunity to control weeds mechanically before crop sowing. Hence, weed diversity, dominance, and community composition vary under CA as compared to the CT. The ZT recorded the highest Shannon index, Pieloús evenness index and species richness over CT which indicates a higher weed species diversity in ZT as compared to CT (Pratibha *et al.,* 2021). In ZT system, 60– 90% weed seed bank is accumulated in the top 5 cm of the soil which results in their even germination and effective control through various techniques. Moreover, surface lying weed seeds under CA are subjected to decay, predation and desiccation due to harsh weather leading to loss of viability (Nichols *et al*., 2015).

Impacts of Conservation Agriculture on Soil Health

Soil physical properties Intensive seedbed preparation and repeated soil disturbance leads to soil structural deterioration and poor physical soil properties which affect plant root growth (Gathala *et al.* 2013). (Das *et al.* 2013) observed that, plots under ZT bed planting had about 5% higher bulk density (BD) compared with CT bed planting plots in the 0–5 cm soil layer, whereas plots under wheat residue recorded 6% lower BD in 0–5 cm soil layer than no residue–applied plots. Higher magnitude of soil penetration resistance in PTR. Crop–residues increased the steady–state infiltration rate by 24% compared to no–residue treatment. (Mohammad *et al.* 2018) reported that, overall soil moisture contents (0– 30 cm) in a triple ZT system which involved mung bean residue + ZT DSR–rice residue + ZT Indian mustard–Indian mustard residue + ZT summer mungbean system was 12.6% higher than PTR–CT Indian mustard treatment. Singh *et al*. (2016) reported that, in the colder winter months (December to February), soil minimum temperature was 1.0 to 3.0°C higher, whereas soil maximum temperature was lower by 2.1 to 7.1°C in the residue retention plots compared to no residue plots. Soil chemical properties and carbon sequestration Improved soil tilth, structure and aggregate stability achieved through CA enhance gas exchange and aeration, which is needed for nutrient cycling (*Das et al*., 2013). Soil pH is influenced strongly by cultivation and crop– residue management, although there are contrasting views. Choudhary *et al.* (2018) reported that, soil pH and electrical conductivity (EC) were lower under ZT + residue than CT in a rice–wheat–mungbean system. Under ZT, nutrients and organic matter tend to accumulate near the soil surface, and in the long–run, soil reaction (pH) gets declined. Sepat et al. (2014) reported that, ZT increased the nitrogen and potassium by 9.6 and 5%, respectively, over the CT plots, while crop–residue increased organic C, nitrogen, phosphorus, and potassium in soil by 7.5, 7, 7.5 and 8.0%, respectively, over no–residue plots. Soil organic matter from residues decomposes at a slower rate under ZT because of less mixing and soil–residue contact, which enhances the SOC over time (Das *et al.,* 2020). Again, CA practices resulted in 26% higher total SOC stock over the CT at 0– 15 cm soil depth, while CA and CT did not differ for SOC stocks at 15–30 cm depth. (Modak *et al.* 2019) reported that the total SOC concentration after 9 years of CA was ~25% higher under ZT than CT in topsoil and residues resulted in 39-58% higher SOC concentration than no-residue plots.

Soil Biology and Biodiversity

Microbiological activities are generally used for assessing soil quality which includes microbial biomass, soil respiration, enzyme activities –dehydrogenase, fluorescein diacetate, Beta–glucosidase, alkaline phosphatase, as well as higher resolution studies such as community profiling by fatty acids, DNA fingerprinting, high–through put sequencing etc. (Jat *et al.,* 2021). Soil microbial biomass (SMB) and microbial enzymes play a pivotal role in maintaining soil health and its environment. Soil organic matter (SOM) is the main determinant of biological activity, because it is the primary energy source for soil fauna and microbes. Stable soil microbial community including beneficial bacterial and fungal species can be developed under CA, which can suppress pathogens. Bacteria, actinomycetes, fungi, earthworms and nematodes were found to be higher in residue–mulched fields than those where the residues were incorporated (Baghel *et al.,* 2018).

Globally, CO_2 is major anthropogenic greenhouse gas (GHG), accounting for 76% of total emission, whereas the contributions of CH_4, N_2O and fluorinated gases (F–gases) are 16, 6.2 and 2.0% respectively (IPCC, 2014). Tillage has a great influence on CO_2 emission which is directly related to frequency of tractor passes across the farm field. The main direct GHG emission from agriculture is $N_2 O$ (from soils, fertilizers, manure, urine of grazing animals) and CH_4 (ruminant animals, rice cultivation), both having higher global warming potential (GWP) than CO_2 (Bhatia *et al.,*2010).

Bottlenecks/Constraints for Adoption of Conservation Agriculture

Despite multifarious benefits, there is slower adoption of CA worldwide except in few countries like Brazil, Argentina, Australia, and the USA owing to various constraints encountered during its adoption. In India for example, ZT was first introduced to farmers in the early 1990s through the CIMMYT sponsored Rice–Wheat Consortium and took almost 20 years to reach 1.5 million ha in 2010 (Sharma, 2021). The major constraints identified for slow pace in adoption of CA are discussed here.

Machines dependence and unavailability at farmer's level

Sowing of seed and fertilizer placement, furrow closing and seed/ soil compaction. Also, there is urgent need of lightweight direct–drill seeder machines for manual, animal or small–tractor power sources with low affordable costs for small–scale farmers, especially in the hills and mountain areas. The operational cost of machinery–intensive CA system may increase over time (Karlen *et al.,* 2013) and result in lower economic benefit. Moreover higher power tractors (>45 HP) are required for operating happy seeders.

Residue unavailability and competitive role

The success of CA depends much on the availability of residues, which varies depending on crops and locations. Crop–residues also have alternate competitive uses, such as feed, fodder and fuel wood in small holder farming systems, especially in mixed crop and livestock systems and under rainfed agro–ecologies, having cropping restricted to single season (Saad *et al.,* 2016). Particularly, residues of certain cereals and legumes provide high value fodder for livestock in small holder farming systems and therefore fodder/ feed is often in critically short supply.

Heavy weed pressure and herbicidal dependence

As perceived by many, higher weed problem especially in initial 3 years and sole dependence on herbicidesis another limitation for adoption of CA. Standing water in puddled transplanted rice (PTR) prevents germination and establishment of weed. Higher herbicide uses and application of same herbicide repeatedly may expedite development of resistance in weeds. Under residue–laden conditions, pre–emergence herbicides are less effective vis–à–vis selective post–emergence herbicides are lacking for many crops.

Yield decline under zero tillage practice in the initial years

Yield declines following ZT practice in first few years may hinder adoption of CA. Most small and marginal farmers cannot risk yield decline in the initial years to venture into a new system. A global meta–analysis involving 6,005 paired yield data obtained from 678 studies across 50 crops and 63 countries revealed that, ZT caused yield reduction in the first few years with up to 5.1% yield decline (Pittelkow et al., 2015). Reduced yield under CA particularly during conversion phase are mainly due to high weed pressure, poor crop stands due to low germination, nutrient immobilization, higher insect–pest and disease attack, waterlogging in poorly–drained soils, lack of skills and knowledge among farmers during initial years etc.

Secondary problems: nutrient immobilization, carry– over pests and pathogens

Addition of huge quantities of crop residues with low C: N, especially cereal straws may lead to net immobilization of soil nutrients in the initial years of CA adoption leading to deficiency symptoms in crops. Increased fertilizer doses are therefore required to sustain crop yields. However, after the initial setback, the soil system reaches a new equilibrium and accumulated SOM leads to net mineralization and release of nutrients in the subsequent years (Erenstein and Laxmi, 2008). Baghel *et al*. (2020) reported higher nematode in CA based DSR under wheat residue leading to yield loss. Large amount of soil organic materials stimulates white grubs or cutworms that cut root of cereals and cause complete yield loss (Jat *et al.,* 2012). Proper planning and implementation of integrated pest management complemented with continuous monitoring and consultation with Krishi Vigyan Kendra (KVK), an agricultural extension centre, and scientists can eliminate such threats. Lack of technical knowledge and management skills CA is management–intensive and necessitates different operational skills than those required under conventional agriculture.

Future Roadmap/ Research Needs

1. There is need of cropping system–based long–term feasibility study of CA under small holders' farms, in a participatory mode, for upscaling of CA technology among farmers.
2. Awareness and adaptive mind set of users are highly essential for adoption of CA. Frequent training, counseling, and working together may improve farmers' acquaintance with CA equipment/ machineries and smoothen CA adoption.
3. Quantification and characterization of crop–residues may be done for better impact under CA. Any arbitrary amount of residue should not be retained, having implications on crop germination and seedlings growth, allelopathy and insect–pests and diseases incidence.
4. There are needs of CA–specific crop varieties, having initial vigorous growth and quick canopy–forming ability and efficient root system best suited to CA system. Also needed are Fe and Zn deficiency tolerant rice varieties for DSR.
5. Crop–residue allelopathy may be quantified on crops, weeds and microbial community structures through long–term studies. Weeds, pests and diseases dynamics over times under CA is of paramount importance.
6. Precision nutrient–management protocols, surface and subsurface drip irrigation for water saving and higher efficiency of Carbon , water and energy footprints and balances with economics.
7. Zero tillage (ZT) practice may be alternated by one year CT after every 5–6 years of ZT (as applicable) with deep summer cultivation, soil solarization etc.
8. Exploring surface vs sub–surface soil C dynamics, microbial community structure , microbiome, and GHGs emissions under CA and linking with soil structural aggregates and pore size distribution.

Conclusion

Food production must be increased by another ~1 billion tonnes by 2050 to feed the burgeoning global population, while restoring the degraded soils and ecosystems, reducing net anthropogenic emissions, and improving the environment. Since resources are limited, there is an urgent need to adopt and promote conservation–effective production practices in agriculture. Conservation agriculture (CA)–based systems play a vital role in sustainable agricultural production. These systems provide a wide range of provisioning (food production, water–use efficiency), regulating (soil–moisture conservation, soil aggregation, groundwater regulation, energy use efficiency, waste decomposition and detoxification, soil–erosion prevention, carbon sequestration, climate regulation) and supporting (nutrient accumulation and cycling, biodiversity conservation, primary production) ecosystem services that are essential to enhance use efficiency of natural resources (soil, water, air, fuel) and to meet environmental and food security goals in accordance with UNDP Sustainable Development Goals. Studies should be focused on CA–based agricultural practices specific to location, cropping system and cropping season and how the ecosystem services are modified by them. Also, there should be clear comparisons on ecosystem services generated by conservation and conventional agriculture over a wide range of soil and climatic conditions, so that assessment of CA can be done better. Doing this can help CA to be adopted widely and sustain the natural resources and productivity on a long–term basis.

Reference

Baghel, J. K., Das, T. K., Mukherjee, I., Nath, C. P., Bhattacharyya, R., Ghosh, S. and Raj, R. 2020. Impacts of conservation agriculture and herbicides on weeds, nematodes, herbicide residue and productivity in direct–seeded rice. *Soil and Tillage Research* 201: 104634.

Baghel, J.K., Das, T.K., Rana, D.S. and Paul, S. 2018. Effect of weed control on weed competition, soil microbial activity and rice productivity in conservation agriculture–based direct–seeded rice (Oryza sativa)–wheat (Triticumaestivum) cropping system. *Indian Journal of Agronomy* 63(2): 129– 136.

Bhatia, A., Sasmal, S., Jain, N., Pathak, H., Kumar, R. and Singh, A. 2010. Mitigating nitrous oxide emission from soil under conventional and no–tillage in wheat using nitrification inhibitors. *Agriculture, Ecosystems and Environment* 136(3– 4): 247–253.

Bhattacharyya, R., Bhatia, A., Das, T.K., Lata, S., Kumar, A., Tomer, R., Singh, G., Kumar, S. and Biswas, A.K. 2018. Aggregate–associated N and global warming potential of conservation agriculture–based cropping of maize–wheat system in the north–western Indo–Gangetic Plains. *Soil and Tillage Research* 182: 66–77.

Bijarniya, D., Parihar, C.M., Jat, R.K., Kalvania, K., Kakraliya, S.K. and Jat, M.L. 2020. Portfolios of climate smart agriculture practices in smallholder rice–wheat system of Eastern Indo- Gangetic plains–crop productivity, resource use efficiency and environmental foot prints. *Agronomy* 10(10): 1561.

Chaudhary, V. P., Singh, K. K., Pratibha, G., Bhattacharyya, R., Shamim, M., Srinivas, I. and Patel, A. 2017. Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation. *Energy* 130: 307–317

Chhokar, R., Sharma, R., Jat, G., Pundir, A. and Gathala, M. 2007. Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. *Crop Protection* 26: 1,689–1,696.

Choudhary, M., Jat, H.S., Datta, A., Yadav, A.K., Sapkota, T.B., Mondal, S., Meena, R.P., Sharma, P.C. and Jat, M.L. 2018. Sustainable intensification influences soil quality, biota, and productivity in cereal–based agroecosystems. *Applied Soil Ecology* 126: 189–198

Choudhary, M., Rana, K.S., Bana, R.S., Ghasal, P.C., Choudhary, G.L., Jakhar, P., and Verma, R.K. 2017. Energy budgeting and carbon footprint of pearl millet–mustard cropping system under conventional and conservation agriculture in rainfed semi–arid agro–ecosystem. *Energy* 141: 1,052– 1,058.

Das, A., Mohapatra, K.P. and Ngachan, S.V. 2018a. Conservation agriculture for restoration of degraded land and advancing food security. (In) *Conservation Agriculture for Advancing Food Security in Changing Climate,* vol. 1, pp. 1–35.

Das, A., Mohapatra, K.P., Ngachan, S.V., Panwar, A.S., Rajkhowa, D.J., Ramkrushna, G.I. and Layek J. (Eds). Today & Tomorrow's Printers and Publishers, New Delhi, India. Das, A., Babu, S., Layek, J., ThoiThoi Devi, M., Krishnappa, R., Ghosh, P.K., Prakash, N. and Ngachan, S.V. 2017. Conservation agriculture for managing degraded lands and advancing Food Security in North Eastern Region of India. *International Journal of Economic Plants* 4 (04): 190–194.

Das, T. K., Nath, C. P., Das, S., Biswas, S., Bhattacharyya, R., Sudhishri, S., Raj, R., Singh, B., Kakralia, S. K., Rathi, N. and Sharma, A. R. 2020. Conservation agriculture in rice– Indian mustard cropping system for five years: impacts on crop productivity, profitability, water–use efficiency, and soil properties. *Field Crops Research* 250: 107781.

Das, T. K., Saharawat, Y. S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K. K., Sharma, A. R. and Jat, M. L. 2018b. Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize–wheat cropping system in the North–western Indo–Gangetic Plains. *Field Crops Research* 215: 222–231.

Das, T.K. and Yaduraju, N.T. 2007. Effect of irrigation and nitrogen levels on grassy weed competition in wheat and comparative eco–physiology of Phalaris minor Retz. and Avenasterilis ssp. ludoviciana Dur in wheat. *Indian Journal of Weed Science* 39(3 & 4): 178–184.

Das, T.K., Bandyopadhyay, K.K., Bhattacharyya, R., Sudhishri, S., Sharma, A.R., Behera, U.K., Saharawat, Y.S., Sahoo, P.K., Pathak, H., Vyas, A.K. and Bhar, L.M. 2016. Effects of conservation agriculture on crop productivity and water–use efficiency under an irrigated pigeonpea–wheat cropping system in the western Indo–Gangetic Plains. *The Journal of Agricultural Science* 154(8): 1,327–1,342.

Das, T.K., Bhattacharyya, R., Sharma, A.R., Das, S., Saad, A.A. and 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.

Das, T.K., Bhattacharyya, R., Sudhishri, S., Sharma, A.R., Saharawat, Y.S., Bandyopadhyay, K.K., Sepat, S., Bana, R.S., Aggarwal, P., Sharma, R.K. and Bhatia, A. 2014. Conservation agriculture in an irrigated cotton–wheat system of the western Indo–Gangetic Plains: Crop and water productivity and economic profitability. *Field Crops Research* 158: 24–33.

Erenstein, O. and Laxmi, V. 2008. Zero tillage impacts in India's rice–wheat systems: A review. *Soil and Tillage Research* 100(1–2): 1–14.

FAO 2017. FAO CA website at: www.fao.org/ag/ca (accessed 17 January 2017).

Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Kumar, V. and Sharma, P.K. 2011. Effect of tillage and crop establishment methods on physical properties of a medium textured soil under a seven year rice–wheat rotation. *Soil Science Society of America Journal* 75(5): 1,851–1,862.

Gathala, M.K., Timsina, J., Islam, M.S., Rahman, M.M., Hossain, M.I., Harun–Ar–Rashid, M., Ghosh, A.K., Krupnik, T.J., Tiwari, T.P. and McDonald, A. 2015. Conservation agriculture based tillage and crop–establishment options can maintain farmers' yields and increase profits in South Asia's rice– maize systems: Evidence from Bangladesh. *Field Crops Research* 172: 85–98.

Ghosh, S., Das, T.K., Rathi, N., Rana, K.S. and Biswas, D.R. 2020. Productivity, profitability and input–use efficiency of direct– seeded rice (Oryza sativa) under conservation agriculture. *Indian Journal of Agricultural Sciences* 90(5): 1004–1008.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, N., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R. and Pathak, H. 2016. Mitigation of greenhouse gas emission from rice– wheat system of the Indo–Gangetic plains: Through tillage, irrigation and fertilizer management. *Agriculture, Ecosystems and Environment* 230: 1–9

Jat, H. S., Choudhary, K.M., Nandal, D.P., Yadav, A.K., Poonia, T., Singh, Y., Sharma, P.C. and Jat, M.L. 2020. Conservation agriculture–based sustainable intensification of cereal systems leads to energy conservation, higher productivity and farm profitability. *Environmental management* 65(6): 774– 786.

Jat, H. S., Datta, A., Choudhary, M., Sharma, P.C., Dixit, B. and Jat, M.L. 2021. Soil enzymes activity: Effect of climate smart agriculture on rhizosphere and bulk soil under cereal based systems of north–west India. *European Journal of Soil Biology* 103: 103292.

. Karlen, D. L., Kovar, J. L., Cambardella, C. A. and Colvin, T. S. 2013. Thirty–year tillage effects on crop yield and soil fertility indicators. *Soil and Tillage Research* 130: 24–41.

Kassam, A., Friedrich, T. and Derpsch, R. 2019. Global spread of conservation agriculture. *International Journal Environmental Studies* 76: 29–51.

Laik, R., Sharma, S., Idris, M., Singh, A.K., Singh, S. S., Bhatt, B. P., Saharawat, Y., Humphreys, E. and Ladha, J. K. 2014. Integration of conservation agriculture with best management practices for improving system performance of the rice–wheat rotation in the Eastern Indo–Gangetic Plains of India. *Agriculture, Ecosystems and Environment* 195: 68–82

Mishra, A.K., Aggarwal, P., Bhattacharyya, R., Das, T.K., Sharma, A.R. and Singh, R. 2015. Least limiting water range for two conservation agriculture cropping systems in India. *Soil and Tillage Research* 150: 43–56.

Modak, K., Ghosh, A., Bhattacharyya, R., Biswas, D.R., Das, T.K., Das, S. and Singh, G. 2019. Response of oxidative stability of aggregate–associated soil organic carbon and deep soil carbon sequestration to zero–tillage in subtropical India. *Soil and Tillage Research* 195: 104370.

Mohammad, A., Sudhishri, S., Das, T.K., Singh, M., Bhattacharyya, R., Dass, A., Khanna, M., Sharma, V.K., Dwivedi, N. and Kumar, M. 2018. Water balance in direct–seeded rice under conservation agriculture in North–western Indo–Gangetic Plains of India. *Irrigation Science* 36(6): 381–393.

Ngwira, A.R., Kabambe, V., Simwaka, P., Makoko, K. and Kamoyo, K. 2020. Productivity and profitability of maize–legume cropping systems under conservation agriculture among smallholder farmers in Malawi. Acta Agriculturae Scandinavica, Section *Soil and Plant Science* 70(3): 241– 251.

Nichols, V., Verhulst, N., Cox, R. and Govaerts, B. 2015. Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* 183: 56–68.

Nyagumbo, I., Mupangwa, W., Chipindu, L., Rusinamhodzi, L. and Craufurd, P. 2020. A regional synthesis of seven–year maize yield responses to conservation agriculture technologies in Eastern and Southern Africa. *Agriculture, Ecosystems and Environment* 295: 106898.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., Pradhan, S., Pooniya, V., Dhauja, A., Chaudhary, V., Jat, M. L., Jat, R. K. and Yadav, O. P. 2016. Conservation agriculture in irrigated intensive maize–based systems of north–western India: Effects on crop yields, water productivity and economic profitability. *Field Crops Research* 193: 104–116.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., Pradhan, S., Pooniya, V., Dhauja, A., Chaudhary, V., Jat, M. L., Jat, R. K. and Yadav, O. P. 2016. Conservation agriculture in irrigated intensive maize–based systems of north–western India: Effects on crop yields, water productivity and economic profitability. *Field Crops Research* 193: 104–116.

Parihar, C.M., Singh, A.K., Jat, S.L., Dey, A., Nayak, H.S., Mandal, B.N., Saharawat, Y.S., Jat, M.L. and Yadav, O.P. 2020b. Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal–based system. *Soil and Tillage Research* 202: 104653.

Pooniya, V., Zhiipao, R. R., Biswakarma, N., Jat, S. L., Kumar, D., Parihar, C. M., Swarnalakshmi, K., Lama, A., Verma, A. K., Roy, D. and Das, K. 2021b. Long–term conservation agriculture and best nutrient management improves productivity and profitability coupled with soil properties of a maize– chickpea rotation. *Scientific Reports* 11(1): 1–13.

Pradhan, A., Chan, C., Roul, P. K., Halbrendt, J. and Sipes, B. 2018. Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: A transdisciplinary approach. *Agricultural Systems* 163: 27–35.

Pratibha, G., Srinivas, I., Madhavi, M., Indoria, A.K., Murthy, K., Reddy, S., Ch, S.R., Biswas, A.K. and Chaudhari, S.K. 2021. Weed shift and community diversity in conservation and conventional agriculture systems in pigeonpea–castor systems under rainfed semi–arid tropics. *Soil and Tillage Research* 212: 105075.

Ram, H., Dadhwal, V., Vashist, K.K. and Kaur, H. 2013. Grain yield and water use efficiency of wheat in relation to irrigation levels and rice straw mulching in North West India. *Agricultural Water Management* 128: 92–101.

Rochette, P. 2008. No–till only increases N2 O emissions in poorly– aerated soils. *Soil and Tillage Research* 101: 97–100.

Rodríguez, E., Fernández–Anero, F. J., Ruiz, P. and Campos, M. 2006. Soil arthropod abundance under conventional and no tillage in a Mediterranean climate. *Soil and Tillage Research* 85(1–2): 229–233.

Saad, A. A., Das, T. K., Rana, D. S., Sharma, A. R., Bhattacharyya, R. and Lal, K. 2016. Energy auditing of a maize–wheat–greengram cropping system under conventional and conservation agriculture in irrigated north–western Indo–Gangetic Plains. *Energy* 116: 293–305.

Sangar, S., Abrol, I. P. and Gupta, R. K. 2005. Conservation agriculture: Conserving resources–enhancing productivity (NoCIS–4419). International Maize and Wheat Improvement Centre, Maxico.

Sepat, S., Behera, U.K., Sharma, A.R., Das, T.K. and Bhattacharyya, R. 2014. Productivity, organic carbon and residual soil fertility of pigeonpea–wheat cropping system under varying tillage and residue management. Proceedings of the National Academy of Sciences, India Section B: *Biological Sciences* 84(3): 561–571

Sharma, A.R. 2021. Conservation agriculture in India: History, progress and way forward. *Indian Journal of Agronomy* 66(1): 1–18.

Singh, V. K., Dwivedi, B. S., Singh, S. K., Majumdar, K., Jat, M. L., Mishra, R. P. and Rani, M. 2016. Soil physical properties, yield trends and economics after five years of conservation agriculture based rice–maize system in north–western India. *Soil and Tillage Research* 155: 133–148.

Singh, Y. and 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): 95–114.

Susha, V. S., Das, T. K., Nath, C. P., Pandey, R., Paul, S. and Ghosh, S. 2018. Impacts of tillage and herbicide mixture on weed interference, agronomic productivity and profitability of a maize–wheat system in the North–western Indo–Gangetic Plains. *Field Crops Research* 219: 180–191.

Susha, V. S., Das, T. K., Nath, C. P., Pandey, R., Paul, S. and Ghosh, S. 2018. Impacts of tillage and herbicide mixture on weed interference, agronomic productivity and profitability of a maize–wheat system in the North–western Indo–Gangetic Plains. *Field Crops Research* 219: 180–191.

Tellez–Rio, A., Vallejo, A., Marco, S.G., Lammerding, D.M., Tenorio, J.L., Rees, R.M. and Guardia, G. 2017. Conservation Agriculture practices reduce the global warming potential of rainfed low N input semi–arid agriculture. *European Journal of Agronomy* 84: 95–108.

Tellez–Rio, A., Vallejo, A., Marco, S.G., Lammerding, D.M., Tenorio, J.L., Rees, R.M. and Guardia, G. 2017. Conservation Agriculture practices reduce the global warming potential of rainfed low N input semi–arid agriculture. European *Journal of Agronomy* 84: 95–108.

Timsina, J. and Connor, D.J. 2001. Productivity and management of rice–wheat cropping systems: issues and challenges. *Field Crops Research* 69(2): 93–132.

Trichard, A., Alignier, A., Chauvel, B. and Petit, S. 2013. Identification of weed community traits response to conservation agriculture. *Agriculture, Ecosystems and Environment* 179: 179–186.

Wang, Q., Lu, C., Li, H., He, J., Sarker, K. K., Rasaily, R. G., Liang, Z., Qiao, X., Li, H. and Mchugh, A. D. J. 2014. The effectsof no–tillage with subsoiling on soil properties and maize yield: 12–Year experiment on alkaline soils of Northeast China. *Soil and Tillage Research* 137: 43–49.

Yadav, G.S., Babu, S., Das, A., Datta, M., Mohapatra, K.P., Singh, R., Singh, V.K., Rathore, S.S. and Chakraborty, M. 2021. Productivity, soil health, and carbon management index of Indian Himalayan intensified maize–based cropping systems under live mulch based conservation tillage practices. *Field Crops Research* 264: 108080.

***