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IMPACTS OF CONSERVATION AGRICULTURE ON SOIL HEALTH AND CROP PRODUCTIVITY: RESEARCH ADVANCES AND ADOPTION BARRIERS IN BANGLADESH

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Abstract

Conservation Agriculture (CA) is a vibrant practice globally to achieve profitable and sustainable crop production with environmental sustainability. Minimum tillage, crop residue retention and diversified crop rotation are the core principles of CA. This practice offers numerous benefits, notably carbon sequestration, reduced GHG emission, improved soil aggregation, increased water use efficiency, and decreased costs of crop production. However, adoption of CA in sub-tropical agro-ecosystems is very low principally due to lack of knowledge, awareness and policy. This review presents a comprehensive analysis of the impact of CA on soil, crops and environment with a focus on CA research and adoption barriers in Bangladesh. An overview of Bangladesh works indicates that the CA practice, depending on the duration of experiment, contributes to C stock in soil at a rate of 0.5-1 t ha^{-1} yr^{-1}. However, magnitude of CA benefits depends on the duration of CA adoption, amount & types of crop residue retention and nature of crop diversifications. Adoption of CA in Bangladesh is low as well as slow which necessitates motivation campaign to the farmers with appropriate policy intervention. Farmers find weed infestation a big constraint which however can be manageable by judicious use of herbicides. The CA practice results in lower or equal crop yield for the first few years; the yield benefit is visible generally after 3-5 years, depending on crop and soil types, when soil quality viz. carbon sequestration, bulk density, water use efficiency are improved. This approach is more suitable to dryland crops (wheat, mustard, pulses), not potato and less to wetland rice. Most CA research is done on single crops and short-term basis; future CA research needs to be directed to a longer-term cropping system and for smallholder farmers. The cropping systems in Bangladesh are predominantly rice based where the increasing scarcity of resources (water, labor and energy) and production costs make this cropping system less profitable and less sustainable. Nevertheless, integrating the suitable crop rotation with CA based best management practices and appropriate tillage machines could be an effective means for sustained crop productivity and economic benefits for smallholder farmers. Hence, appropriate government policy support is needed for increasing adoption of CA by the farmers.

Keywords: CA adoption, CA benefits, CA research, Crop residue, Crop rotation, Zero tillage

1. Fundamentals of Conservation Agriculture

1.1 Concept of CA

Conservation Agriculture (CA) is a concept that aims to achieve improved and sustained crop productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO, 2014a). Thus, it is a good practice for Sustainable Land Management (SLM). CA is a base for sustainable and profitable crop production and it complies with the ideas of ecological sustainability (Kassam *et al.,* 2009; Friedrich, 2013; Jat *et al.,* 2014). Conservation Agriculture enhances biodiversity and biological processes above and below the ground surface. Soil interventions such as mechanical tillage are reduced to a minimum or zero, and external inputs such as agrochemicals and plant nutrients of mineral or organic origin are applied optimally and in ways and quantities that do not interfere with, or disrupt, the biological processes (FAO, 2014a).

1.2 Principles of CA

Conservation Agriculture is characterized by three linked principles (FAO, 2014b):

- No or minimal mechanical soil disturbance

  That is no-till and sowing or broadcasting of seeds or direct placing of planting materials in the soil; in special cases limited strip or band seeding disturbing less than 30% of the soil surface, as opposed to repeated ploughing.
- Maintenance of an organic soil mulch cover, especially by crop residues, crops or cover crops, as opposed to burning or removing them.
- Diversification of crop species grown in sequence or associations through rotations or, in case of perennial crops, associations of plants, including a balanced mix of legume and non-legume crops, as opposed to growing non-legume crops in a rotation.

1.3 Benefits of CA

There are numerous medium- to long-term benefits of CA, as follows:

(i) Decreased production costs (Crabtree, 2010; Hossain, 2024);

(ii) Improved soil quality which refers to the soil's physical, chemical and biological characteristics (Rekwar *et al.* 2024);

(iii) Long-term C sequestration and increased soil organic matter (Saharawat *et al.,* 2012; Corsi *et al.,* 2012);

(iv) Improvement of water and nutrient use efficiencies (Jat *et al.,* 2012; Saharawat *et al.,* 2012),

(v) Enhancement of production and productivity @ 4-10% (Kader *et al.,* 2022; Gathala *et al.,* 2011),

(vi) Timely sowing of seeds (Malik *et al.,* 2005; Johansen *et al.,* 2012);

(vii) Reduced greenhouse gas emissions and improved environmental sustainability

(Rahman *et al.,* 2024; Yue *et al.,* 2023; Huang *et al.,* 2011),

(viii) Avoiding crop residue burning, which reduces nutrient loss and pollution (Sidhu *et al.,* 2007);

(ix) Opportunities for crop diversification and intensification (Jat *et al.,* 2005);

(x) Reduced loss of nitrogen for slow breakdown of plant residues resulting in slow release of mineralizable N (Kassam *et al.,* 2009; Alam *et al.,* 2020);

(xi) Limited weed seeds stay in the sub-surface layer, which hardly germinate from the deep soil and thus weed seed bank ultimately is diminished (Zahan *et al.* 2021; Steckel *et al.,* 2021).

2. Brief History of CA Adoption

2.1 Global context

Tillage posed questions for the first time in the 1930s, when the dustbowls devastated wide areas of the mid-west United States. The concept for reducing tillage and keeping soil covered came up and the term conservation tillage was introduced. Seeding machinery development occurred in the 1940s to seed directly in the field without any soil tillage. Then, theoretical concept resembling today's CA principles was elaborated by Edward Faulkner in his book "Ploughman's Folly" (Faulkner, 1945) and Masanobu Fukuoka with the "One Straw Revolution" (Fukuoka, 1975). But it was not until the 1960s for no-tillage to enter into farming practice in the USA (Kassam *et al.,* 2014a). Then it took another 20 years before CA reached a significant level of adoption. From the early 1990s CA started growing exponentially, leading to a revolution in the agriculture of southern Brazil, Argentina and Paraguay. During 1990s the CA concept attracted attention of the other parts of the world, including international research organizations such as FAO, World Bank, GIZ, CIRAD, CIMMYT and CGIAR. Adoption of CA started in industrialized countries after the end of the millennium, particularly in Canada, USA, Australia, Spain, Italy, Finland, Ukraine and Russia. Few crops like root and tuber crops are not a good fit to CA system (Derpsch and Friedrich, 2009). More recently, to address soil erosion and drought problems along with increasing cost of energy and production inputs, government support has played an important role in accelerating the adoption rate of CA, leading to the relatively fast adoption for example in Kazakhstan and China.

Globally, CA adoption is increasing at a rate of 10 m ha annually. Adoption of this practice was less than 1 m ha in 8 countries in 1970 to 205 m ha in 102 countries in 2019 which was 15% of the world's cropland area. In Argentina, Australia, Brazil, Canada, Paraguay, South Africa, Uruguay and the USA, the CA methods are applied on more than half their cropped area (Kassam, 2022).

2.2 Bangladesh context

CA has emerged in South Asia (nine countries including Bangladesh) as an alternative to intensive tillage (Chaudhary *et al.,* 2022), however, the area under CA in South Asia remains relatively low and its adoption is also slow (Fig. 1) compared with many other regions having similar climatic conditions (Somasundaram *et al.,* 2020). However, adoption of CA in Bangladesh is far less than other Asian countries like China and India accounting for less than 1%.

The CIMMYT-Bangladesh first introduced CA based tillage technology in the farmers' field for wheat crops in late 90's with minimum tillage by 2WT operated seeder (Miah *et al.,* 2017) and introduced Chinese seeder in 1995 in this country. Later in 2002, Bangladesh Agricultural Research Institute (BARI) developed and patented BARI Seeder (PTOS) including inclined plate seed metering device suitable for minimum, strip and zero tillage for seeding of all upland crops. The BARI also developed BARI Seeder Bed Planter in 2007 and Zero till planter in 2015. Recently 4WT has been developed for the same purpose. Besides PTOS, Versatile Multi-crop Planters (VMP) has been developed with a provision of multiple crop establishment options including zero tillage, strip tillage, single pass shallow tillage on the flat together with bed planting (both new and permanent beds), and even conventional tillage, seeding and fertilizer application options (Hossain *et al.,* 2015; Haque *et al.,* 2011; Hossain, 2023). Photographs of strip tillage, bed planting and zero tillage crop cultivation methods are provided in the Fig. 2.

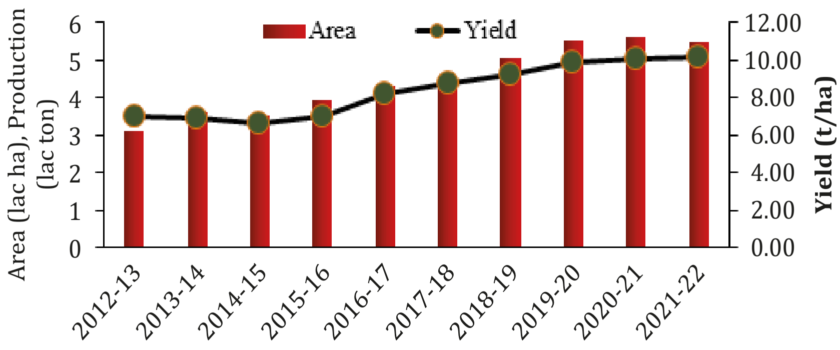


Fig. 1 *Long-term strategic research on CA based sustainable intensification in wheat and maize based systems – initiated by CIMMYT Bangladesh in 2009*

(Source: Gathala, 2023)

Strip tillage Bed planting Zero till maize

Fig. 2 *Strip tillage, bed planting and zero tillage cultivation systems*

3. Impact of CA on Soil Health

Minimum tillage creates impact on the physical, chemical and biological properties of soil (Franzluebbers, 2002), however, its extent depends on soil texture, climate, cropping system, residue volume, soil's initial status, and duration of this practice (Lal, 1997). Conservation agriculture is a good solution to restore and preserve soil quality (Sharma *et al.,* 2019). It is vitally important to develop strategies for sustainably increasing food production without affecting soil health (Montpellier Panel, 2014).

Saurabh *et al.* (2021) used SQI (soil quality index) as an instrument based on physical [macro aggregate stability (MAS), available water capacity (AWC) and soil penetration resistance (SPR)], chemical [soil organic carbon (OC), available N, available P 0and available K] and biological [microbial biomass carbon (MBC), fluorescein diacetate (FDA) and dehydrogenase activity (DHA)] properties of soil; SQA calculated by PCA. After a meta-analysis, they found soil properties like MAS, OC, MBC, FDA and DHA higher by 47, 18, 56, 48 and 53%, respectively, under ZTDSR-ZTW (T_7: Zero-till direct seeded rice - Zero-till wheat) than RPTR-CTW (T_1: Random puddled transplanted rice - Conventional till broadcasted wheat), at 0-10 cm. The higher system rice equivalent yield of 12.41 t ha^{-1} was observed at SQI value of 0.90 at 0-10 cm and 0.86 at 10-20 cm in T_7 treatment.

3.1 Soil bulk density and aggregation

Minimum tillage with retention of crop residues decrease soil bulk density (Topa *et al.,* 2021), showing a 0.8-1.5% lower (Zhang *et al.,* 2009) or by 0.05 g cm^{-3} lower (Ghuman AND Sur, 2001) as compared to conventional tillage (CT) with no residue. Xu and Yao (1988) in China, Zeleke *et al.* (2004) in Ethiopia, and Singh *et al.* (2007) in India measured significant decreases in BD after 3-5 years of crop residue incorporation. However, from a global analysis Li *et al.* (2020) concluded an increased bulk density for no-tillage and commented experimental duration be the predominant factors controlling the response of soil properties to NT practice.

Compared with conventional tillage (CT), no tillage (NT) with straw mulching (SS) increases the macro-aggregates (> 0.25 mm) by 12–26% (Liu et al. 2023). Zhang *et al.* (2009) and Jahangir *et al.* (2021) also reported better aggregation and stability in CA tillage plots. Long-term ZT along with optimum nutrient and residue management enhances soil SOC concentration, in turn leading to favorable alterations in soil aggregation, hydraulic conductivity, porosity and moisture retention (Bhattacharyya *et al.,* 2019; Dey *et al.,* 2020). More immediate effect of balanced nutrition in CA can be visible through improvement of microbial biomass carbon (MBC), soil microbial diversity and enzymatic activities (Dey *et al.,* 2016).

3.2 Soil carbon sequestration

Generally, soil organic carbon (SOC) increases in CA plots (Choudhary *et al.,* 2018). It is reported to be 7.3% higher SOC than in intensively plowed plots at 0-20 cm depth (Chen *et al.,* 2009). Many other researchers have also reported a positive effect of minimum or no tillage on SOC (Piazza *et al.,* 2020; Adak *et al.,* 2023; Linsheng *et al.,* 2024). Adoption of long-term (15 years) zero or reduced tillage with residue incorporation led to a 15.8–25.7% increase in SOC stock compared to CT-R (conventional tillage with residue incorporation (Fagodiya *et al.,* 2024). Based on meta-analysis Wang *et al.* (2021) state that straw returning to the field significantly increases SOC content by an average of 13.97% ± 1.38% (n = 446) and its variation depends on temperature, initial SOC content, duration of straw return (maximum in 6-9 years) and cropping systems. CA can help sequester carbon in soil at a rate of 0.2 to 1.0 t ha^{-1} yr^{-1}, as observed by several researchers (Sá *et al.,* 2013; Corsi *et al.,* 2014). For IGP regions Powlson *et al.* (2016) have reported an annual increase in SOC stock between 0.16 and 0.49 Mg C $ha^{-1}yr^{-1}$ in CA plots. As observed in Bangladesh the CA practice depending on the duration of experiment contributes soil C stock at a rate of 0.5-1 t $ha^{-1}yr^{-1}$ (Alam *et al.,* 2020, Jahangir *et al.,* 2021; Islam *et al.,* 2022; Kader *et al.,* 2022; Kumar *et al.,* 2022; Maniruzzaman, 2022).

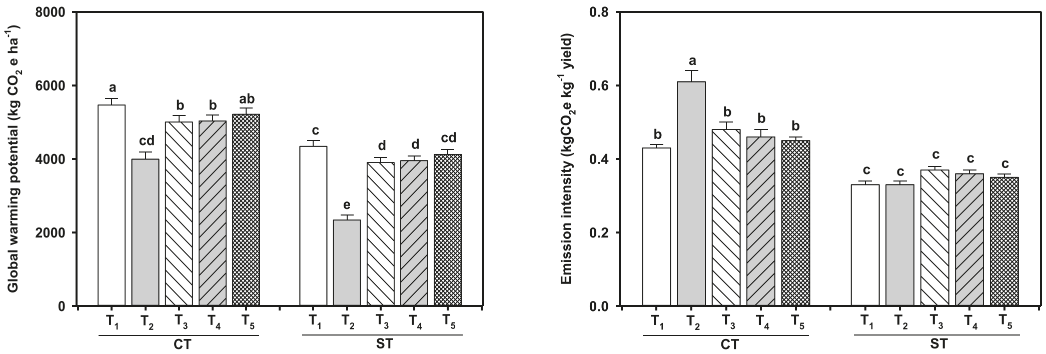
Long-term ZT along with residue management can enhance the concentration as well as stability of SOC (Bhattacharyya *et al.,* 2013; Parihar *et al.,* 2019; Jat *et al.,* 2019) and the SOC content within macro-aggregates could be 25-30% higher in the ZT plots than in CT at 0-15 cm soil depth (Modak *et al.,* 2020). After 10 years of crop rotation, plots under no-till and chisel plow treatments in 0–10 cm depth, had 7–13%, 34–35% and 9–15% higher non-labile fraction, very-labile fraction and TOC, respectively compared to conventional tillage (Topa *et al.,* 2021). Several studies indicate that the additional C accumulated under CA practices such as no-till is concentrated in particulate organic fractions or other pools considered 'labile', with only marginal increases in more recalcitrant pools (Bhattacharyya *et al.*, 2012; O'Rouke *et al.,* 2015). Long-term ZT along with optimum nutrient and residue management enhances the soil SOC concentration as well as its stability (Parihar *et al.,* 2019; Dey *et al.,* 2020). The CA reported to achieve annual C-sequestration rate as high as ~1.15 Mg ha^{-1} yr^{-1} under PB-SSNM, which indicated better stabilization of SOC under CA-based precision nutrient management (Parihar *et al.,* 2020). Choudhary *et al.* (2018) observed higher SOC and MBC in ZT than in CT and in HR than LR in Indo-Gangetic Plains under rice cropping system.

A review of temperate region studies showed the impact of cereal straw incorporation on SOC content to be small and often non-significant, even when continued for up to 25 years (Powlson *et al.,* 2011). The rate of residue decomposition, and hence SOC accumulation, is more sensitive to environmental conditions (temperature, moisture) for surface-applied residues, as in CA, than for those that are incorporated (Helgason *et al.,* 2014). Smaller SOC increases are expected in tropical regions compared to temperate due to more rapid decomposition under higher mean temperatures (Powlson *et al.,* 2011). Conservation tillage usually leads to the accumulation of SOM in the topsoil (Piazza *et al.,* 2020), the effects of rhizospheric microbial hot zone and nutrient leaching on enzyme activities should not be underestimated (Wang *et al.,* 2023). Dolan *et al.* (2006) also observed that surface soil (0–20 cm) yielded 30% more SOC with NT than CT, but this tendency was reversed at a soil depth beyond 20 cm, possibly due to inversely squeezed residue.

Linsheng *et al.* (2024) observed a positive effect of conservation tillage (minimum or no tillage) on SOM, microbial carbon and nitrogen via promoting soil enzyme activity with slope ranging from -0.07 to 0.94, as evidenced from a meta-analysis. In addition to CA impact on crop yields, it is very often reported that CA mitigates climate change by sequestering organic C in soil (Jat *et al.,* 2012; Lal, 2015; UNEP, 2013), though the experimental evidence for this is mixed and causes controvers0y (Powlson *et al.,* 2014, 2015; Neufeldt *et al.,* 2015). A meta-analysis shows that crop residue addition leads to C sequestration in China, however its potential is offset when residue substantially increases soil emission of N_2O (potential GHG) that also depends on the quantity and types of residues showing emission factor varying from 0.62 to 2.8% (Chen *et al.,* 2013)

3.3 GHG emission

In CT the NH3 emission ranged from 14 to 17% while in ST it varied between 16 and 21% (Uddin *et al.,* 2021, Fig. 3). Higher NH_3 emission in ST with residue incorporation is caused mainly by stoichemical changes in soil bio-physico-chemical conditions, especially redox chemistry and pH. However, these changes are needed to investigate further in different agroecosystems and cropping patterns. In potato field, crop residue incorporation reduces NH_3 emissions but in maize fields they increase it (Jahangir *et al.,* 2022).



CT=Conventional tillage, ST=Strip tillage, T_1= +NPKZn, T_2= -N+PKZn, T_3= -P+NKZn, T_4= -K+NPZn, T_5= -Zn+NPK

Fig. 3 *CA shows 24.5% less carbon footprint and 28.5% less emission intensity or global warming potential than CT. Source: Gathala, 2023.*

In a situation with high rates of N fertilizer, a combination of no-till and straw retention led to a decrease in N_2O emission, with similar or increased crop yields compared to conventional tillage with straw removed (Aryal *et al.,* 2016; Huang *et al.,* 2015). CA can decrease greenhouse gas emissions (GHG) relative to conventional puddling and transplanting (Alam *et al.,* 2016, 2019). In maize-wheat system, the zero tilled permanent broad bed (PBB) with residue (R) retention had significantly improved SOC pool at 0–30 cm soil layer compared to CT (Das *et al.,* 2018). Greater N_2O fluxes occurred in CT (conventional tillage) than in CA (conservation agriculture) based systems. Parihar *et al.* (2018) observed higher SOC and lower N_2O fluxes in MWMb (maize-wheat-mungbean) and MCS (maize-chickpea-sesbania) than in MMS (maize-maize-sesbania) cropping system.

Reduced tillage or no-tillage combined with straw return is more effective in increasing activity of most of soil enzymes, but temperature and edaphic factors modulate the response of soil enzymes to conservation tillage (Jahangir *et al.,* 2021; Wen *et al.,* 2023). Annual temperature, annual precipitation, soil pH and straw size are the key factors for CH_4, N_2O, CO_2 and GWP, respectively. Straw return amount, straw size and straw return method optimization could reduce GWP. Amount of straw ≥ 7500 kg ha^{-1}, size ≥ 5 cm and incorporation are suggested to reduce GWP (He *et al.,* 2024). Reduced tillage increases GHG (N_2O and CH_4) emissions and decreases crop yields, whereas no- tillage decreases GHG emissions, with no effect on crop yield (Yue *et al.,* 2023). Reduced tillage increases N_2O emissions in temperate wheat field (Jahangir *et al.,* 2011) and also in subtropical wheat-mungbean-rice system (Jahangir *et al.,* 2021). Crop residue incorporation and reduced tillage effects GHG emissions still remain in debate which may depend on soil, agroclimatic and cropping systems suggesting requirement of more regional data for developing appropriate management strategies.

3.4 Non-puddled transplant rice yields

Puddling is a traditional practice of tilling saturated soil for cultivating wetland rice. It helps water retention by breaking capillary tube and also helps weed control. On the negative side, puddling destroys soil aggregates and macropores, causes soil compaction, and decreases water permeability due to formation of a hard plough pan zone in the subsurface layer (Alam *et al.,* 2020; Jahangir *et al.,* 2021).

In addition, it can restrict root development and water and nutrient use as in the rice-wheat cropping system (Gathala *et al.,* 2011), though some reports do not support this view (Humphreys *et al.,* 2005). These negative effects are impacted on the dry season crops (e.g. wheat, maize, lentil etc.) following rice. The hard plough pan increases bulk density and soil penetration resistance, and reduces hydraulic conductivity and macroporosity of soil (Gathala *et al.,* 2011; Chauhan *et al.,* 2012).

In the Indo-Gangetic Plain regions, rice crop in CA fields is established by dry direct seeding method, SRI method or machine transplanting method (Jat *et al.,* 2014; Saurabh *et al.,* 2021, Magar *et al.,* 2022). However, in Bangladesh, recently non-puddled manual transplanting system for rice has been developed (Haque *et al.,* 2016; Bell *et al.,* 2019; Salahin *et al.,* 2021; Kader *et al.,* 2022) which involves strip tillage (ST), irrigation to saturate and soften the soil for 18 to 24 hours and then transplanting seedlings in the strips. Rice grown with single pass wet tillage and maize grown with strip tillage gave the highest gross margin over time, but tillage methods and residue treatment produced no significant grain yield differences (Islam *et al.,* 2015).

3.5 Crop productivity

CA farming supports long-term crop yield and factor productivity (FAO, 2011) with environmental and economic advantages. Jat *et al.* (2019) reported significantly higher system productivity from a 10-year old CA-experiment under zero tillage (ZT) or permanent bed (PB) compared with conventional tilled (CT) system in eastern IGP. Practising zero tillage (ZT) in flat and permanent raised beds (PB), combined with balanced fertilization often proved beneficial in sub-tropical Indian soils in several wheat-based cropping systems (Jat *et al.* 2019; Parihar *et al.,* 2019). Parihar *et al.,* (2016) showed that SSNM (site-specific nutrient management) based nutrient application coupled with CA-based tillage practices in maize-wheat-mungbean system produces higher system productivity.

Many reports suggest that the transition from CT to no-till decreased yield in early years until increases in soil C, aggregate stability, and water holding capacity (Kumar *et al.,* 2012; Alam *et al.,* 2020). From a global meta-analysis (63 countries representing 50 crops -rice, wheat, maize, oilseeds, legumes, etc.), Pittelkow *et al.* (2015) concluded that no-tillage system was the 4th most influential variable, with a lag period of several years (5+ years) occurring before no-till yields matched CT yields and legumes and wheat performed better under no-till system relative to the results reported for rice. Positive yield response in non-puddled rice also took six years in the Bangladesh study (Kader *et al.* 2022; Farooq *et al.,* 2011). CA tillage reduces land preparation cost (water, labor and energy savings), irrigation cost and increases economic yield relative to conventional tillage (Bell *et al.,* 2019; Jat *et al.,* 2019; Salahin *et al.,* 2021.). System productivity and net returns under PB + MB (permanent bed + mungbean) were significantly increased by 28.2–30.7% and 36.8–40.5% compared to CT, respectively in north-west IGP of India (Jat *et al.,* 2018).

Zero tillage with residue retention had a mean yield advantage of 5.8%, a water use efficiency increase of 12.6%, an increase in net economic return of 25.9% and a reduction of 12–33% in global warming potential in maize–wheat systems (Jat *et al.,* 2020). Increasing topsoil depth supported significantly increased grain yield of maize which was related to positive changes in crop physiology (root surface area, LAI, photosynthetic rate, etc.). The lowest yield was noted in S1 (10 cm soil depth) and the highest in S5 ¬¬¬ (50 cm depth) (Zhang *et al.,* 2024). Guo *et al.* (2020) observed a 9-22% yield loss in maize when tillage depth was reduced from 30 cm to 10 cm. Zero-tillage and crop residue retention led to increased crop productivity together with increased TOC (12%) and increased available P, K and Zn contents (11-16%) over conventional tillage with removal of residues (Nandan *et al,* 2019).

3.6 Rice water requirement

Long-term CA reduces plough pan formation as it avoids puddling and therefore soils remain undisturbed. Removal of plough pan gradually increases soil water percolation and thus enhances irrigation water requirement of rice. However, in region where ground water table is deeper reduced tillage may help enhance groundwater recharge and storage. In dry period or in the drought prone regions CA can increase soil water storage by enhancing water percolation and redistribution or storage in the soil profile which will reduce soil water deficit. Moreover, in other than rice, increased water percolation may increase crop yields by enhancing availability of residual water. In the CA systems, this is, by far, the most interesting area of research which needs to be explored. The water and crop economy of the removal of plough pan in rice fields are also unknown. Hydrological characterization and soil-groundwater hydrology in CA systems need more attention for exploring the benefits of CA which can be region and crop specific.

4. Advances of CA Research in Bangladesh

Recent studies in the EGP (Eastern Gangetic Plains - southern Nepal, north-eastern India and Northern Bangladesh) suggests that CA plays a significant role in enhancing crop productivity growth, resource use efficiency and soil and water quality and reduces production costs in comparison with non-CA practices (Islam *et al.,* 2019; Gathala *et al.,* 2020; Keil *et al.* 2020).

CA performed better than CT in different winter crops and cropping systems but not in monsoon rice; however alternate tillage (rice tilled and wheat, maize, mungbean untilled) can be an alternative option (Hoque *et al.,* 2023). Scope exists to intensify the cropping systems and practise triple cropping systems, especially by including short-duration pulses (mungbean), oilseeds (mustard), and fiber crop (jute) in the EGP (Islam *et al.,* 2019, Islam *et al.,* 2022: Rashid *et al.,* 2019).

Repetitive tillage requires intensive water and energy use (Islam *et al.,* 2019) and emits large amounts of greenhouse gases (Jat *et al.,* 2020). Research in south Asia has shown that CA or strip tillage (ST), with residue retention, commonly results in greater yields and profits from non-rice crops compared to rice (Islam et al., 2019; Akter *et al.,* 2021). Rice seedlings can be transplanted without puddling, which thus helps save water, energy, labor, and overall production cost for rice cultivation (Haque *et al.,* 2016, Hossen *et al.,* 2018). The review of several recent studies established that heavy soils (silty clay loam) had either lower or equal rice yield (−6.1 to 2.3%) under no-till (non-puddled) system compared to conventional puddled system than lighter soils (sandy loam) where rice yield reduction was about 10%, which can be attributed to higher percolation rate and low nitrogen use efficiency (Chaki *et al.,* 2021), nevertheless rice yield penalty (<5%) was compensated by higher yields of the succeeding dry season crops (Rashid *et al.,* 2019; Hoque *et al.,* 2023) in northwest Bangladesh. The Government of Bangladesh is now promoting agricultural mechanization through a mega subsidy scheme (National Agricultural Mechanization Policy, 2020).

Both minimal soil disturbance and increased crop residue retention, core components of CA, increased S pools in soils primarily due to increased SOC sequestration (Kumar *et al.,* 2022). Adoption of CA practices by farmers in the intensive rice-based triple-cropping systems on the EGP is slowly increasing (Bell *et al.,* 2019; Haque *et al.,* 2016) and the CA practices not only increase crop yield but also mitigate the effects of rice-based cropping systems on greenhouse gas emission (Alam *et al.,* 2016). In addition, minimal soil disturbance and increased residue retention practiced for 5 years increased soil organic carbon (SOC) (0–10 cm soil depth) by 68% in intensive triple-cropping, rice-based cropping systems on the Grey Terrace soil of the EGP (Alam *et al.,* 2018). Since SOM is a chief source of N, P & S and CA practices add organic matter to soil, thus its (SOM) decomposition is likely to alter forms and availability of N, P & S in soil. Very recently several contract projects and PhD student's research indicate that CA practice depending on the duration of experiment could contribute soil C stock at 0.5-1 t ha^{-1} yr^{-1} (Alam *et al.,* 2020, Jahangir *et al.,* 2021; Islam *et al.,* 2022;

Kader *et al.,* 2022; Kumar *et al.,* 2022; Maniruzzaman, 2022). In silt loam soil, the ZT

UPTR (zero till unpuddled transplanted rice) performed similar grain yield and gave higher water productivity compared to PTR (puddled transplanted rice), but in sandy loam soil the PTR showed better results (Chaki *et al.,* 2021).

5. Barriers of CA practices in Bangladesh

Many scientists and extension specialists raise several issues with zero tillage (ZT) in terms of diseases, insects, perennial weeds, soil compaction, nutrient immobilization, persistence of pesticide residues, and buildup of surface crop residues (Hobbs and Govaerts, 2010). Perhaps one of the biggest barriers to the widespread adoption of CA is to convince the farmers that satisfactory crop production is achievable with minimal or no tillage and crop residue retention, beyond the advantages of its potential to lower production costs. The Followings are the major barriers of CA adoption in Bangladesh (Jat *et al.,* 2014; Paz *et al.,* 2024):

- Lack of farmers awareness and mind set about CA practice and its benefits;
- Farmers' perception (tradition) about necessity of ploughing and leveling of land;
- A yield penalty in the first few years (3-5 years) for rice is one of the issues that need to be considered for policy framing on CA. However, in other than rice, the yield under CA increases from the beginning which can be a trade-off and be a compensation for crop rotation in CA. In addition, government can compensate such yield loos for rice to farmers who are practicing CA for rice.
- Unavailability of appropriate planting equipment/seeders, particularly for small and medium-sized farmers (Magar *et al.,* 2022);
- Lack of government subsidy to purchase CA machines;
- Widespread use of crop residues for animal feed, fuel and roofing material as well as burning the residue for timely seeding of the following crop;
- More suitable to dryland crops (e.g. wheat, mustard, pulses) and less to wetland rice;
- Unavailability of more crop options and rotations;
- CA may produce lower yield for the first few years;
- Lack of skilled and scientific manpower, as well as adequate technical advisors, to provide quality technical assistance and training to the farmers;
- Weed infestation is a big constraint to the adoption of CA practice in the initial years; however it eventually ceases since weed seed bank is reduced with advancement of cropping (Zahan *et al.* 2021).
- Unavailability of suitable herbicides and alternative management strategies for weed management; herbicide resistance may build up.

6. Analysis of results from global and regional CA practices

Reduced tillage intensity and prolonged growing period of cover crops could limit declines in soil organic matter and soil biota while maintaining soil structure and crop yield (Sleiderink *et al.,* 2024). Conservation Agriculture (CA) practice, especially after 3-5 years, is widely observed to increase crop yields, reduce soil degradation and develop systems that are more resilient to stresses caused by climate change (Kassam *et al.,* 2009; Thierfelder and Wall, 2009; Jat *et al.,* 2012). Most progress in CA has been made in large-scale commercial agriculture based on mechanized farming principles which are not yet adopted widely in rice-based cropping systems in Asia (Kassam *et al.,* 2015). Although CA shows great promise in diverse agro-ecological environments, there is serious debate about its practical feasibility under certain farmer circumstances, especially for smallholders in mixed crop/livestock systems in tropical regions, where there is competition for crop residues between their utilization as animal feed. In Bangladesh, the CA adoption is slow since the farmers are not yet fully convinced of its long-term benefits in respect of sustained soil health and crop productivity. Besides this, they find several constraints such as weed pressure, lack of land leveling, inaccessibility of appropriate machines, and lack of zero tillage service providers. Thus, integrating the best compatible cropping patterns accompanied by best management practices into the portfolio of farmers' own technologies would improve system productivity, resource use efficiency and economic profitability (Alam *et al.,* 2015).

Evidently large amount of research has been done on a single crop, as in temperate countries (Pittelkow *et al.,* 2015) and in South Asia (Magar *et al.,* 2022), not in any annual cropping system. Thus, future research in Bangladesh needs to be oriented over annual cropping system, although CA practice is more promising for non-rice crops e.g. wheat, pulses, mustard, but not potato. Hence, the continuing spread of CA globally is creating a need for effective national and regional policy and institutional support (Kassam *et al.,* 2014b). As stated by (Bell *et al.,* 2019), adoption of CA in the rice-wheat cropping system with the inclusion of pulses may lead to a greater sustainability of the CA system through increased SOC accumulation and lower C input to maintain soil health.

In the Eastern Gangetic Plains of Bangladesh, the cropping systems are predominantly rice based, having large yield gaps in farmers' fields because of poor management practices adopted by farmers. The increasing scarcity of resources (water, labor and energy) and production costs further make the rice-based cropping system less sustainable and less profitable. There is a need of highly productive, resource efficient and sustainable crop rotations and management practices that are adapted to the changes in agricultural, socioeconomic and climatic environment. Integrating the appropriate crop rotation accompanied by BMPs and CA into the portfolio of farmers' own technologies are crucial for maximizing productivity and economic benefits to the farmers (Ladha *et al.,* 2009). There is also a need for breeding and selection of a rice plant type suitable for direct seeding after zero tillage in heavy-textured soils (Islam *et al.,* 2015).

7. Conclusions

Minimal soil disturbance, crop residue retention and legume-based crop rotation, the core components of CA, help increase crop productivity primarily due to SOC sequestration and decreased cost of production. The magnitude of benefits depends on the duration of CA adoption and amount & types of crop residue retention. The CA approach is more applicable to dryland crops (wheat, mustard, pulses), and less to wetland rice. Adoption of CA in Bangladesh is slow and farmers' and scientists' hesitation to accept this approach is a major factor for it suggesting exploration of the benefits of CA in wider agroclimatic conditions and cropping systems. Weed infestation, unavailability of appropriate CA machines and rice (75% area coverage) being the dominant crop are the major constraints to the farmers' adoption of CA. The full benefits of CA are not visible before 3-5 years during the time carbon sequestration and some other soil properties have improved. Most CA research is done on single crops and short-term, future CA research should be directed to a longer-term cropping system and for smallholder farmers. Hence, appropriate government policy support is important for increasing adoption of CA by the farmers.

Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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