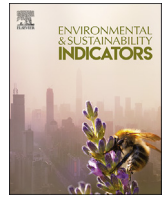


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## Conservation tillage (CT) for climate-smart sustainable intensification: Assessing the impact of CT on soil organic carbon accumulation, greenhouse gas emission and water footprint of wheat cultivation in Bangladesh

MD Mashiur Rahman<sup>a,\*</sup>, Sreejith Aravindakshan<sup>b</sup>, Muhammad Arshadul Hoque<sup>c</sup>,  
 Mohammad Arifur Rahman<sup>d</sup>, Md. Ashrafuzzaman Gulandaz<sup>c</sup>, Jubaidur Rahman<sup>e</sup>,  
 Md. Tariqul Islam<sup>f,1</sup>

<sup>a</sup> Agricultural Engineering Division, Regional Agricultural Research Station, Bangladesh Agricultural Research Institute, Jamalpur, 2000, Bangladesh

<sup>b</sup> Farming Systems Ecology, Wageningen University and Research, Droevendaalsesteeg 1, Wageningen, 6708PB, the Netherlands

<sup>c</sup> Farm Machinery and Post-harvest Process Engineering Division, Bangladesh Agricultural Research Institute, Gazipur, 1701, Bangladesh

<sup>d</sup> Soil Science Division, Regional Agricultural Research Station, Bangladesh Agricultural Research Institute, Jamalpur, 2000, Bangladesh

<sup>e</sup> Agronomy Division, Regional Agricultural Research Station, Bangladesh Agricultural Research Institute, Jamalpur, 2000, Bangladesh

<sup>f</sup> Director, Research Wing, Bangladesh Agricultural Research Institute, Gazipur, 1701, Bangladesh

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### ABSTRACT

Soil organic carbon (SOC), greenhouse gas (GHG) emissions and water footprint (WF) are the key indicators of environmental sustainability in agricultural systems. Increasing SOC while reducing GHG emissions and WF are effective measures to achieve high crop productivity with minimum environmental impact (i.e. a multi-pronged approach of sustainable intensification (SI) and climate-smart agriculture (CSA) to achieve food security). In conventional agricultural systems, intensive soil tillage and removal of crop residues can lead to increase negative environmental impact due to reduce SOC, GHG emission and high water consumption. Conservation agriculture (CA) based conservation tillage systems (CTS) with crop residue retention is often suggested as a resource conserving alternative to increase crop productivity without compromising soil health and environmental sustainability of cereal cropping systems. The environmental impact of CTS in terms of SOC, WF and GHG emissions nonetheless remains understudied in Bangladesh. A two-year field experiment was carried out to evaluate the impacts of CTS with retention of crop residue on SOC accumulation, GHG emission and WF in wheat cultivation of Bangladesh. In the experiment, CTS such as zero tillage (ZT) and minimum tillage (MT) were compared with the conventional tillage (CT) practice. Result observed that the SOC accumulation in the soil was  $0.11 \text{ t ha}^{-1}$ ,  $0.97 \text{ t ha}^{-1}$ , and  $1.3 \text{ t ha}^{-1}$  for CT, MT and ZT practices, respectively. A life cycle GHG emission estimation by farm efficiency analysis tool (FEAT) calculated 1987, 1992 and 2028  $\text{kg CO}_2\text{eq ha}^{-1}$  for ZT, MT and CT practices, respectively. Among the studied tillage options, lowest WF was achieved by MT ( $570.05 \text{ m}^3 \text{ t}^{-1}$ ) followed by ZT ( $578.56 \text{ m}^3 \text{ t}^{-1}$ ) and CT ( $608.85 \text{ m}^3 \text{ t}^{-1}$ ). Since the results are in favor of CTS, this study recommends MT and ZT practice to reduce negative environmental externalities in wheat cultivation in Bangladesh. In comparison between the methods, the MT, which retains crop residue (20 cm), and involves principles of CA, is suitable for both CSA and SI of wheat cultivation in Bangladesh due to its ability to increase SOC accumulation, prevent both water loss, and GHG emission without compromising yield.

\* Corresponding author.

E-mail address: [mashi.fpm84@gmail.com](mailto:mashi.fpm84@gmail.com) (M.M. Rahman).

<sup>1</sup> Dr. Md. Tariqul Islam is working as the of Bangladesh Agricultural Research Institute (BARI), Gazipur-1701, Bangladesh. He leads BARI's research programmes and activities through 6 special crop research centres, 17 research divisions, 8 regional research stations, and 28 sub-stations. He oversees a team of scientists and supporting staff involved in sustainable agriculture development in Bangladesh. Besides, he has published widely in international journals, and has authored many books and research briefs, and has participated in developing several agricultural decision support tools for Bangladesh.

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## 1. Introduction

Wheat (*Triticum aestivum* L.) is the second most important cereal crop next to rice (*Oryza sativa* L.) in Bangladesh (Sayed et al., 2020). Wheat is grown in rotation with rice in Bangladesh. Rice is typically grown during June to October, followed by wheat in the cooler and drier winter season known as ‘rabi’ (November–April). This intensive production rotation, which relies predominantly upon excessive soil tillage, high inputs, nutrients and water have resulted in a number of biophysical production constraints including declining soil fertility, moisture stress, receding groundwater table, greenhouse gas (GHGs) emissions and lower crop yields (Alam et al., 2014; Bijarniya et al., 2020). These constraints have been accentuated by the region's increased poverty, farmers' low investment capacity and increasing energy and input costs, in addition to climatic variability (Lopez-Ridaura et al., 2018).

As one of the most climate vulnerable countries in the world, wheat cultivation in Bangladesh suffers from erratic rainfall, temperature extremes, increased salinity, drought, floods, soil erosion and tropical storms. While in the coastal region where cyclones and extreme weather events are a concern (Aravindakshan et al., 2020), or in north western Bangladesh where drought is more frequent (Qureshi et al., 2015), wheat cultivation suffers multiple climate risks. Temperature and rainfall are the most significant factors affecting wheat growth and soil nutrient absorption (Arshad et al., 2017). Higher temperatures and precipitation increases microbial decomposition of soil organic carbon (SOC) affecting the nutrient exchange between roots and soil water (Deb et al., 2015; Keesstra et al., 2016). Microbial activity and mineralization of SOC compounds tend to hasten under high temperature and aerobic conditions prevailing in sub-tropical humid climate in Bangladesh, leading to higher CO<sub>2</sub> flux to the atmosphere (Alam et al., 2014; Reicosky et al., 1997). On top of these, farmers' practice of crop residue removal during land preparation prevents organic matter buildup in the soil. Subsequent tillage and inversion of soil results in losses of SOC through physical breakdown of any remaining residues (Angers and Eriksen-Hamel, 2008). Resulting depletion of available SOC is a major threat to increasing crop productivity in Bangladesh (Lal, 2015; Van Beek et al., 2019).

Amid declining soil fertility and SOC loss, intensive tillage and application of high inputs in conventional crop management have not resulted in productivity growth or yield increase. Instead, such practices have contributed to high levels of greenhouse gas (GHG) emissions from agriculture. For instance, Bangladesh emitted 190 million metric tons (Mt CO<sub>2</sub>eq) in 2012, with the agriculture sector contributing nearly 40 percent to overall emissions (Climatelinks, 2021). Agricultural land use contributed 19–20% of global GHG emissions including those from the application of chemical fertilizers (nitrous oxide), and land preparation and intensive tillage (FAOSTAT, 2020; Jantke et al., 2020). By 2030, emission reductions of agricultural methane emissions up to 48% and nitrous oxide emissions by up to 26%, relative to 2010 will be required to limit global warming to 1.5 °C (Jantke et al., 2020). Bangladesh targets to reduce 15 percent of its annual GHG emissions arising from agriculture and livestock through the development of a climate-smart agriculture investment plan (Worldbank, 2019).

While GHG emission and soil organic matter (SOM) depletion are mainly due to the nature of crop management and tillage practice, a major part of the GHG emissions in agriculture can be directly linked to irrigation pumping and water withdrawal (Kashyap and Agarwal, 2021). For example, paddy and wheat have the highest water footprint, with the largest emission releasing cultivation practices (Kashyap and Agarwal, 2021; Mekonnen and Hoekstra, 2011). In major wheat producing districts of Bangladesh, groundwater is the primary source of irrigation, while a part of the withdrawal is also used by households for drinking and cooking purposes. At the farm level, irrigation water tend to be managed ineffectively in wheat production, and this has posed a serious problem with groundwater depletion in Bangladesh (Qureshi et al., 2015). Depletion of groundwater resources along with pollution by arsenic and heavy metals, low rainfall in dry climates and lack of access

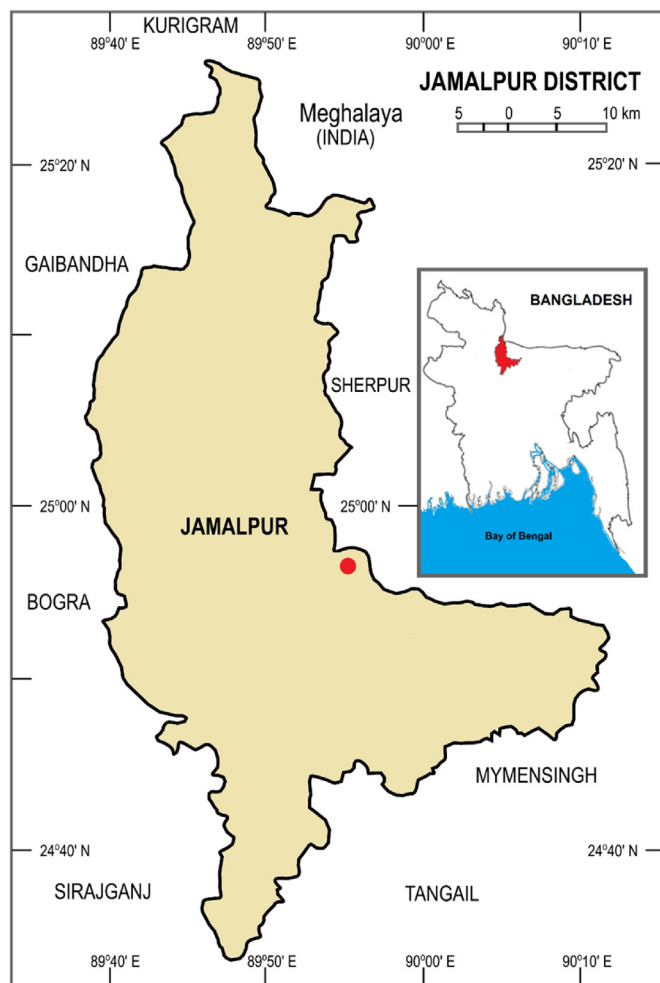


Fig. 1. Location of the experimental site (red dot): Jamalpur in Bangladesh. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

to pump surface water point to the need of sustainable development of water systems in Bangladesh.

Sustainable farming practices that conserve resources such as water and fertilizer inputs while improving SOC and reducing GHG emission have to be adopted in response to soil fertility loss and climate change mitigation. In this regard, the ‘sustainable intensification’ (SI) approach and ‘climate-smart agriculture’ (CSA) that are highly complementary to each other are gaining popularity in agricultural policy circles of Bangladesh (Worldbank, 2019). SI approach entails increasing food production from existing farmland in ways that have lower environmental impact, while CSA is concerned with increased adaptive capacity and reduction of GHG emissions. Conservation agriculture (CA) based conservation tillage systems (CTS) combine the principles of both these approaches through a multi-pronged strategy. For instance, CTS is laid out on three practices promoted as a means for sustainable agricultural intensification: minimum tillage, mulching with crop residue, and crop rotation (Michler et al., 2019). CTS is also widely considered as part of the solution that can contribute to the CSA objectives of i) raising productivity and household income, ii) enhancing adaptation and resilience, and iii) reducing GHG emissions from agriculture (Abegunde et al., 2019; Thierfelder et al., 2017). Cultivation of other cereals, pulses and oilseed can also be successfully achieved under CA based conservation tillage systems (CTS).

Several studies note the potential of CA for improving crop yield, energy and technical efficiency in cereal systems, while maintaining the long-term environmental sustainability of agricultural systems

**Table 1**  
Characteristics of the study field under tillage trials of wheat cultivation.

Parameters	Details	
Location	Regional Agricultural Research Station (RARS), Jamalpur, Mymensingh division, Bangladesh	
Soil type	Silt clay loam	
Location	24° 56' 11" N latitude, 89° 55' 54" E longitude	
Altitude	16.46 m above MSL	
Rainfall (avg.)	Monsoon (June–September) 1549.45 mm	Dry-winter (November–March) 440.00 mm
Drainage	Moderate	
Temperature	32 °C (Max), 20 °C (Min)	

**Table 2**  
Tillage treatments in the study.

Crop	Conservation tillage practices	Residue management
Wheat	<p>T<sub>1</sub> = Zero Tillage (ZT), no disturbances of the soil, power tiller operated inclined plate planter is used for seed sowing operation</p> <p>T<sub>2</sub> = Minimum Tillage (MT), single tillage and the sowing operation performed at once by power tiller operated inclined plate planter</p> <p>T<sub>3</sub> = Conventional Tillage (CT), farmers practice, usually three to five times tillage with power tiller followed by hand sowing</p>	Stubble crop residue (20 cm)

(Aravindakshan et al., 2015, 2018, 2020; Kassam et al., 2013; Malobane et al., 2020). Experiments have also shown a potential reduction of 50% in GHG emissions by efficient utilization of fertilizers, and adoption of conservation agriculture (CA) and resource conservation technologies in the cultivation of wheat in India (Sapkota et al., 2019). Pathways of increasing SOC in conjunction with reducing WF and GHG emissions have gained popularity as effective measures to achieve high crop productivity with minimum environmental impact (i.e., a multi-pronged approach of sustainable intensification (SI) and CSA to achieve food security). But these key indicators of environmental sustainability in agricultural systems viz. SOC, GHG emission and WF are rarely studied in wheat cultivation under different tillage systems. Therefore, a two-year experimental study has been carried out with the objective of evaluating the impact of alternative tillage options in wheat cultivation such as (1) CA based different CTS practices (zero tillage (ZT) and minimum tillage (MT)) and (2) conventional tillage (CT) on SOC accumulation, GHG emission and water footprint (key indicators of environmental sustainability) and crop yield.

## 2. Materials and methods

### 2.1. Experimental location and climate

The field experiment was carried out in the research field at Regional Agriculture Research Station (RARS), Jamalpur, Bangladesh (Fig. 1) to assess the SOC, GHG emission and WF of different tillage practices of

wheat cultivation. The experiment was conducted during the *rabi* season for two-consecutive years (2019–2020). The experimental site falls under the agro-ecological zone 9 (old Brahmaputra floodplain) of Bangladesh, where the climate is semi-arid monsoon and sub-tropical. Additional geophysiological characteristics of the study site is in Table 1.

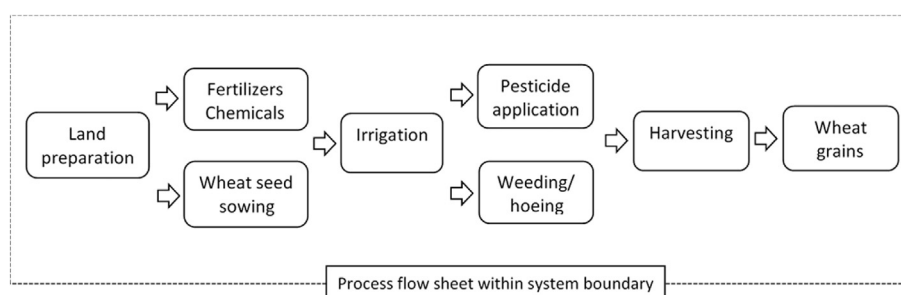
### 2.2. Experimental treatments and design

Adopted design for the experiment was randomized complete block design (RCBD) with three replicates for each treatment. This experiment considered nine fairly large experimental plots of unit area 195.0 m<sup>2</sup> (15.0 m × 13.0 m). A space of 1.5 m was left between the experimental plots and outside border of the plots to avoid any fringe effect or effect from other plots. Each repetition (plots) was surrounded by bunds (*als*) that were 30 cm wide, and 15 cm tall to prevent any seepage loss of soil nutrients. See supplementary material SM1 for details. Experimental treatments were based on different tillage practices with the retention of crop residue from previous rice at a height of 20 cm (Table 2). For sowing, the most popular bread wheat variety of Bangladesh namely BARI Gom 28 (*Triticum aestivum* L.) was selected.

### 2.3. Tillage, sowing, water and fertilizer management practices

The entire production process of wheat cultivation that was carried out in the experiment is provided in Fig. 2. The experimental plots as per design for different treatments and tillage practices were prepared seven days before sowing. The previous rice stubble crop residue (20 cm) was retained in the soil. For zero tillage (ZT) practice, power tiller operated inclined plate planter was used for land preparation and seed sowing (Hossain et al., 2015). For this, tine of inclined plate planter was set at twelve tines for tilling purpose and six rows for seed sowing. The seed metering device was adjusted to maintain the line to line distance of 20 cm. The tillage operation was performed only in lines whereas the other areas were kept untilled. Soil was ploughed up to 6–7 cm depth in lines and wheat seeds were sown by seed metering device into these split opened lines. The seed rate was calibrated according to the standard seed rate of 120 kg ha<sup>-1</sup> prescribed by BARI.

In minimum tillage (MT) practice, soil tillage operation was performed at a minimum level in order to pulverize soil together with stubble crop residue including weeds. This practice is specially adopted for managing weed biomass because weeds can be fully incorporated into the soil that is advantageous to increase the SOC accumulation in the soil (Moyer et al., 1994). Tillage and sowing operations were performed together by BARI inclined plate planter having 48 tines similar to the procedure followed for ZT practice. The difference between these two tillage practices lies in the nature and frequency of tillage operations; sowing operation in lines using twelve tines were carried out for ZT practice without any soil tillage whereas soil tillage up to 6–7 cm depth for the entire plot of 195 m<sup>2</sup> is carried out using 48 tine for MT practice. Tillage and sowing operations for both these CTS options were carried out by employing a single operator and half-a-day's labour. The conventional tillage (CT) practice is also known as farmer tillage practice and



**Fig. 2.** Production process flow sheet for wheat cultivation.

**Table 3**  
Physico-chemical properties of soil at the experimental site (before tillage).

a) Soil physical properties														
Soil depth (cm)	Bulk density (g cm <sup>-3</sup> )	Particle density (g cm <sup>-3</sup> )	Porosity (%)	Infiltration (mm h <sup>-1</sup> )	Field capacity (%)	Textural Class								
0–30	1.40	2.62	46.81	8.50	29.41	silt clay loam								
b) Soil chemical properties														
Sample	pH	OM (%)	OC (%)	Ca	Mg	K	Total N (%)	P	S	B	Cu	Fe	Mn	Zn
				meq 100g <sup>-1</sup>				µg g <sup>-1</sup>						
Sample 1	6.60	1.56	0.91	6.00	1.90	0.07	0.08	5.36	5.45	0.32	2.40	24.00	4.00	1.22
Sample 2	6.40	2.44	1.42	6.00	1.90	0.01	0.12	4.26	12.08	0.32	2.40	24.00	4.00	1.22
Mean	6.50	2.00	1.16	6.00	1.90	0.12	0.10	4.81	8.765	0.32	2.40	24.00	4.00	1.22
Critical level	–	–	–	2.00	0.50	0.12	–	10.00	10.00	0.20	0.20	04.00	1.00	0.60
Interpretation		L	L	O	H	L	VL	L	O	L	VH	H	O	H

Note: L = low, O = optimum, VL = very low, H = high, and VH = very high values in terms of wheat growth.

is most commonly used for intensive tillage in wheat cultivation of Bangladesh. In this experiment, conventional tillage practice was performed up to 10 cm by power tiller where soil was pulverized five times in order to remove the weed biomass and crop residues from the topsoil. This was followed by broadcast sowing of seeds.

Based on the soil fertility tests conducted at the experimental site, the inorganic fertilizer rate of N<sub>120</sub>P<sub>108</sub>K<sub>80</sub>S<sub>85</sub>Zn<sub>10</sub>B<sub>5.2</sub> was applied. Urea (one third) with triple superphosphate (TSP), muriate of potash (MoP), gypsum (CaSO<sub>4</sub>·H<sub>2</sub>O), zinc (ZnSO<sub>4</sub>) and boron (B<sub>2</sub>O<sub>3</sub>) were broadcasted in the soil at the time of land preparation. The remaining half of urea was applied at 25 days after sowing (DAS) and the rest was applied at 45 DAS. Every split of urea fertilizer application was followed by irrigation. Intercultural operations were performed by the weeder machine when necessary. Weeds in ZT treatment plots were controlled partially by spraying a post-emergence selective herbicide ‘affinity (Carfentrazone ethyl + Isoproturon)’ @ 2.5 g/L water, spraying at 25 DAS, followed by a single hand weeding at 28 DAS for the complete elimination of weeds. The soil moisture was monitored regularly by the gravimetric method (Black, 1965). Irrigation operations were performed three times during the whole period. Irrigation water was applied based on the different growth stages of wheat (sowing, milking and heading) considering the DAS. First irrigation was applied after sowing to facilitate proper seed germination and the second irrigation was applied at the milking stage after 25 the DAS and the third and final irrigation was applied at heading stage (51 DAS). Controlled volumetric gauging system was employed to measure the applied irrigation water. Harvest operations were carried out by a combine harvester (16 hp) and plot level wheat and straw yield was recorded. At each stage of tillage operation, fuel measurement and time for tillage were recorded after accounting for time losses throughout the entire operation (Alam et al., 2019).

#### 2.4. Soil sampling and analysis

The soil samples were collected at a depth of 0–20 cm in pre-sowing and post-harvesting stages and analyzed for its physicochemical properties. The soil properties that were collected before land preparation is shown in Table 3. The soil physical and chemical properties were analyzed using standard methods proposed by Olsen et al., (1954) and Page et al., (1989). Soil organic carbon (SOC) accumulation is a dynamic continuous process and the SOC accumulation rate for tillage treatments is not same throughout the different stages from initial soil condition and after crop harvesting. Therefore, soils in the depth of 0–20 cm from each treatment were collected and analyzed for SOC content before sowing, after harvest, and during the growing periods of wheat cultivation. The wet oxidation method was followed to determine SOC content in soil (Jackson, 1959). Moisture content of soil was computed following gravimetric method (Page et al., 1989). The bulk density and particle density was determined by means of adopting standard methods (Olsen et al., 1954; Page et al., 1989). Soil porosity was computed as the

correlation between bulk and particle density employing Equation (1); where, BD stands for bulk density (g cm<sup>-3</sup>) and PD stands for particle density (g cm<sup>-3</sup>).

$$\text{Porosity (\%)} = \left(1 - \frac{BD}{PD}\right) \times 100 \quad (1)$$

#### 2.5. Assessment of GHG emission and carbon footprint

Farm energy analysis tool (FEAT) is a static, deterministic whole-farm modeling approach within the life cycle analysis framework. FEAT is used to evaluate greenhouse gas (GHG) emission and energy consumption of agriculture production process, within a given system boundary (treatment plots of different tillages in this experiment) (Camargo et al., 2013). The latest version of FEAT developed in 2018 was used in the analysis. The FEAT tool has simple interface and better data assimilation and accuracy of estimation compared to other similar tools. Employing FEAT, for each of the treatments, the total GHG emission (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) to produce one functional unit of wheat production was estimated by feeding the input and output data, and emission factors (EF). Emission factors (EF) of the Intergovernmental Panel on Climate Change (IPCC) locally relevant for wheat cultivation of Bangladesh was used in the FEAT tool for calculation of total GHG emissions (TGHG). The SOC accumulation per unit land (SOCA) was calculated by soil analysis as explained in section 2.4. The TGHG can be reported either in CO<sub>2</sub> equivalent (CO<sub>2</sub>eq) or using global warming potential (GWP) based on the EF of IPCC (Stocker et al., 2013). Standard unit of kilogram of Carbon dioxide equivalent (kg CO<sub>2</sub>eq) was used to estimate direct and indirect GHG emission from the use of farm inputs. For the tillage treatments, GHG emission (CO<sub>2</sub>eq) to produce each functional unit of wheat was determined on the basis of GWP value for 100-years (Stocker et al., 2013). The emission factors 25 and 298 were used for accounting CH<sub>4</sub> and N<sub>2</sub>O, respectively (Stocker et al., 2013). The TGHG emissions overestimate the C footprint in the long term when significant SOC differences emerge among cropping and soil management practices (Alam et al., 2019). So, the net life cycle GHG emission (NGHG) for different tillage treatments in the experiment was determined by subtracting accumulated SOC as in equation (2).

$$\text{NGHG} = \text{TGHG} - \text{SOCA} \quad (2)$$

where,

$$\begin{aligned} \text{NGHG} &= \text{Net life cycle GHG emission, (t CO}_2\text{eq ha}^{-1}\text{)} \\ \text{TGHG} &= \text{Total GHG emission, (t CO}_2\text{eq ha}^{-1}\text{)} \text{ and} \\ \text{SOCA} &= \text{SOC accumulation per unit land (t CO}_2\text{eq ha}^{-1}\text{)}. \end{aligned}$$

Carbon footprint (CF) for different tillage options is calculated as GHG emission intensity, i.e. GHG emitted per unit of wheat grains produced.

**Table 4**

Comparative Results of different tillage practices with residue retention on soil physical properties.

Treatment	Soil depth (cm)	Bulk density (g cm <sup>-3</sup> )	Particle density (g cm <sup>-3</sup> )	Porosity (%)	Field capacity (%)
Initial soil	0–20	1.400	2.62	46.81	29.41
ZT (T <sub>1</sub> )	0–20	1.396	2.61	46.83	29.39
MT (T <sub>2</sub> )	0–20	1.385	2.61	47.05	29.86
CT (T <sub>3</sub> )	0–20	1.376	2.61	47.66	30.36
CV (%)	–	0.780	0.21	00.84	01.54
LS	–	NS	NS	NS	NS

\*CV = Coefficient of variance, LS = Level of significance, NS = Non-significant.

## 2.6. Assessment of water footprint and water use efficiency (WUE)

Water footprint (WF) for wheat cultivation was calculated by the summation of green water footprint (GWF) and blue water footprint (BWF). It is the amount of water supplied to produce a crop yield and is usually expressed in equation (3) by m<sup>3</sup> t<sup>-1</sup> (Aldaya et al., 2010; Ewaid et al., 2019).

$$WF = GWF + BWF \quad (3)$$

where GWF is the ratio of the green water consumption by dividing the crop yield (t ha<sup>-1</sup>). Green water consumption is the amount of water that comes from rainwater and soil moisture consumed by crops in their cultivation period, and BWF is the ratio of the blue water consumption by dividing the crop yield (t ha<sup>-1</sup>). Blue water consumption is the amount of water consumed as irrigation water from surface water and groundwater during the cultivation period.

$$GWF = \frac{\text{Green water consumption (m}^3 \text{ ha}^{-1}\text{)}}{\text{Wheat yield (t ha}^{-1}\text{)}} \quad (4)$$

$$BWF = \frac{\text{Blue water consumption (m}^3 \text{ ha}^{-1}\text{)}}{\text{Wheat yield (t ha}^{-1}\text{)}} \quad (5)$$

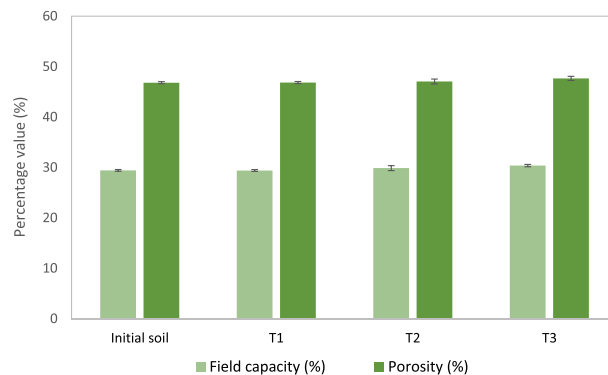
Water use efficiency (WUE) of different treatments were calculated as the ratio of the yield of wheat grains divided by total water used in the production system and it is denoted by water productivity (Zhao et al., 2019).

## 2.7. Data collection

Data collection procedure followed standard methods prescribed for agronomic field experiments (Hunt et al., 2001). Data of wheat grains and biomass residues were collected by selecting five 1.0 m<sup>2</sup> areas followed by quadrates at each sub-plot. In order to collect the necessary data, the wheat crop was cut down above the ground level. Crop cuts were followed by separation, cleaning and drying. The collected wheat grains were put into the oven at 60 °C for 24 h to achieve proper moisture content and dry grain weight was recorded. The same procedure was followed for wheat biomass residues. Standard methods were also followed for determining the yield and yield parameters: plant population (m<sup>2</sup>), plant height (cm), spike area (m<sup>2</sup>), spike length/plot, and no. of spiklet/spike, grains/spike, 100 grain weight (g) and yield (t ha<sup>-1</sup>). The yield and yield parameters from the three replications were used for computing standard deviation (SD), standard error (SE) and least significant differences (LSD) (±, if any) for different tillage treatments.

## 2.8. Data analysis

Statistical analysis of the yield and yield parameters obtained from different tillage treatments were carried out in the computing software 'STAR' developed by International Rice Research Institute (IRRI).



**Fig. 3.** Tillage practices effect along with field capacity and soil porosity. [Legend: T<sub>1</sub>-Zero tillage (ZT); T<sub>2</sub>-Minimum tillage (MT); T<sub>3</sub>-Conventional tillage (CT)].

Analysis of variance (ANOVA) tests were employed to identify significant differences (of  $\alpha = 0.05$ ) between treatments and the DMRT (Duncan's Multiple Range Test) method was employed to compare the obtained data. Means were compared using LSD at 5% level of probability.

## 3. Results and discussion

### 3.1. Conservation tillage impact on soil physical properties

Physico-chemical properties of the soil at the trial field before carrying out the tillage operations are provided in Table 3, whereas Table 4 is shows the Results of different tillage treatments on soil physical properties.

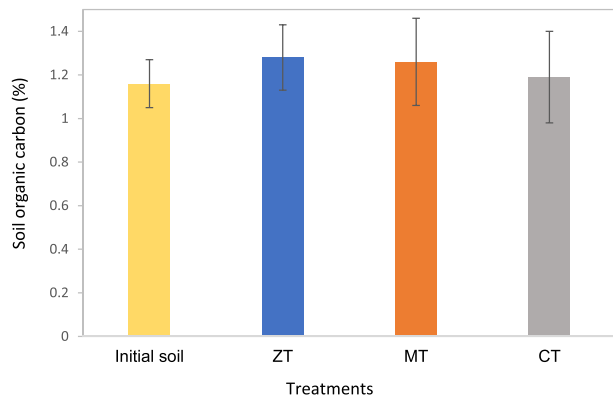
Results show that there is no significant difference between the tillage treatments at a depth of 0–20 cm particularly in the surface and sub-surface layers. The value of bulk density (BD) is almost near the standard value, which lies between 1.47 and 1.50 g cm<sup>-3</sup> (Mukul and Henry, 2016). Soils tend to respond to physical properties differently and properties may be altered by different tillage practices. Soil bulk density (BD) decreased with the depth and difference in tillage practices. Intensive tillage can make the soil loose and porous there by decreasing the BD. Lowest and highest field capacities (FC) and porosities were exhibited by ZT and CT practices, respectively (Table 4 and Fig. 3). Large FC and porosity values indicate the soil's low water holding capacity and vulnerability to soil moisture loss. Soils under CT practice with large values of FC and porosity would require frequent irrigation to prevent yield loss, which in turn may increase production cost of CT practice than CTS practices (Sayed et al., 2020). Under conditions of low soil moisture, low rainfall, and high temperatures, conventional tillage can affect soil structure by inducing slacking and dispersal, mechanical perturbation, and compaction, thus limiting soil nutrient absorption (Reubens et al., 2007). Bulk density, which is closely related to soil structural features and SOM, depends on the method of cultivation (Post et al., 1982). No significant difference in terms of BD was noted between the tillage practices in this experiment. However, long-term conservation tillage with crop residue retention can improve soil bulk density by the addition of organic matter, which can reduce soil compaction (Gelybó et al., 2018; Jat et al., 2018) and better root growth.

Conservation tillage systems (CTS), i.e. the ZT or MT practice which comprises of no or single pass of tillage operation when compared to CT practice with several tillage passes had comparatively lower and better soil physical properties (Table 4). Results show that CTS may be adopted by farmers in marginal soils to enhance soil structure and texture (soil density, soil porosity and field capacity) (Jat et al., 2013; Singh et al., 2016). In fact, CTS such as ZT and MT practice with crop residue retention are advantageous in improving soil quality and decreasing bulk density (Gathala et al., 2011; Govaerts et al., 2009).

**Table 5**  
Wheat yield results and yield contributing characters under different tillage practices.

Treatment	Plant population (m <sup>2</sup> )	Plant Height (cm)	No. of Spike (m <sup>2</sup> )	Spike Length (cm)	No. of Spikelet/Spike	No. of Grain/Spike	1000 grain wt. (g)	Grain Yield (t ha <sup>-1</sup> )	Straw Yield (t ha <sup>-1</sup> )	Harvest Index
ZT (T <sub>1</sub> )	291.00 <sup>b</sup>	92.05	290.12	10.65 <sup>a</sup>	18.07 <sup>a</sup>	46.7	47.87	4.02 <sup>a</sup>	5.36 <sup>a</sup>	0.43
MT (T <sub>2</sub> )	293.00 <sup>b</sup>	92.70	293.25	10.43 <sup>a</sup>	18.15 <sup>a</sup>	46.75	47.97	4.08 <sup>a</sup>	5.48 <sup>a</sup>	0.43
CT (T <sub>3</sub> )	314.00 <sup>a</sup>	90.82	262.25	9.54 <sup>b</sup>	17.07 <sup>b</sup>	46.37	47.15	3.82 <sup>b</sup>	5.02 <sup>b</sup>	0.43
CV (%)	0.83	1.86	6.46	2.78	1.70	0.97	1.24	2.66	2.23	0.43
LSD (0.05)	4.32	–	–	0.49	0.53	–	–	0.18	0.20	–
LS	*	NS	NS	*	*	NS	NS	*	*	NS

Note: ANOVA (0.05) followed by DMRT was used on the data. LSD stands for least significant difference, where similar superscribed letter in the column denotes no significant difference. LS = level of significance, NS = Non-significant, \* = Significant ( $p \leq 0.05$ ).



**Fig. 4.** SOC accumulation under adopting of different tillage practices. ZT = Zero tillage; MT = Minimum tillage; CT=Conventional tillage practice.

### 3.2. Conservation tillage impact on crop productivity and wheat yield

Table 5 shows the wheat yield and yield contributing characters under different tillage practices. Most of the yield contributing characters such as plant population, spike length, grain yield and straw yield varied significantly between tillage treatments (Table 5). The rest of the characters were insignificant. Treatments MT and CT recorded the highest (92.7 cm) and lowest plant height (90.82 cm), respectively which are statistically identical. Wheat yield obtained from different tillage treatments varied significantly. Highest yield was obtained for MT practice (4.08 t ha<sup>-1</sup>) while the lowest was for CT practice (3.82 t ha<sup>-1</sup>).

Table Results indicate that changing the frequency of tillage (i.e., minimum/zero tillage with less soil disturbance) and optimum seed rate (line sowing) could be beneficial in adverse biophysical conditions and may be adopted as a climate change adaptation strategy. In locations where there are high chances of drought or moisture stress may yield better under CTS than CT. Nonetheless, the agronomic interventions alone are not sufficient to facilitate agricultural systems' adaptation and mitigation to climate change in Bangladesh; rather, comprehensive and integrated development programs including extension, credit, and asphalted roads are required to assist in the adoption of sustainable crop management (Aravindakshan et al., 2021) such as CTS.

**Table 6**  
SOC accumulation and Net life cycle CF in wheat production.

Treatment	Total GHG emission (kg CO <sub>2</sub> eq ha <sup>-1</sup> )	Life cycle CF (kg CO <sub>2</sub> eq kg <sup>-1</sup> of grain)	Wheat yield (kg ha <sup>-1</sup> )	SOC (t ha <sup>-1</sup> )	SOC accumulation (t ha <sup>-1</sup> )	GHG emission reduction due to SOC accumulation (kg CO <sub>2</sub> eq ha <sup>-1</sup> )	Net GHG Emission (kg CO <sub>2</sub> eq ha <sup>-1</sup> )	Net Life cycle CF (kg CO <sub>2</sub> eq kg <sup>-1</sup> of grain)
Initial soil	–	–	–	12.992	–	–	–	–
ZT	1987.220	0.495	4014.87	14.295	1.300	4.886	1982.340	0.493
MT	1992.010	0.488	4082.60	13.961	0.970	3.633	1988.370	0.487
CT	2028.280	0.531	3820.55	13.100	0.110	0.403	2027.880	0.531

### 3.3. Conservation tillage impact on SOC accumulation

The conservation tillage systems (CTS) with crop residue retention significantly ( $p < 0.05$ ) increased the total organic carbon (TOC) content in the soil (Fig. 4). Generally, the topsoil within the ranges of 0–50 cm is where majority of SOC gets accumulated in soil. At this portion of the topsoil, over the two years' time period of experimentation, the soil organic carbon (SOC) accumulation rate was estimated at 0.11 t ha<sup>-1</sup>, 0.97 t ha<sup>-1</sup> and 1.3 t ha<sup>-1</sup> for CT, MT and ZT practices, respectively. During this period, SOC contents of 1.19%, 1.26% and 1.28% were observed in the soils under CT, MT and ZT practices, respectively. The SOC content of ZT practice (1.28%) was found statistically different ( $p < 0.05$ ) from CT practice at 5% level. From the initial values of SOC present at the trial plots prior to tillage experiment, the SOC increased by 3%, 9% and 10% after the harvest of wheat under CT, MT and ZT practices, respectively. Previous studies also reported similar significant effect on SOC accumulation for soils under conservation tillage practices (Baker et al., 2007; Begum et al., 2018; D'Haene et al., 2009). Soil carbon dynamics was greatly influenced by tillage operations, crop residue disintegration and soil moisture content. Conventional tillage hastens soil carbon mineralization, which in turn would reduce wheat growth and yield by limiting the availability of soil water for roots. SOC sequestration due to both GHG emission reduction and SOC accumulation was the highest under ZT (4.9 kg CO<sub>2</sub>eq ha<sup>-1</sup>), followed by MT (3.6 kg CO<sub>2</sub>eq ha<sup>-1</sup>) and CT (0.403 kg CO<sub>2</sub>eq ha<sup>-1</sup>) (Table 6). Climate change induced droughts and erratic rainfall can worsen water availability for Bangladesh agriculture during the dry *rabi* season. Water scarcity issues in dry season necessitates the development and adoption of adaptation measures that prevents both residual soil moisture loss and improves soil water holding capacity. Conservation tillage with residue retained had better soil aggregate and soil structure, which in conjunction with SOC, improved porosity and BD, and hence prevented residual moisture loss. Better SOC with improved soil physical properties under CTS is reported to enhance soil aeration and better infiltration of irrigation water (Busari et al., 2015). Results indicate that, among the potential climate smart sustainable intensification strategies in Bangladesh, CTS that comprises of minimal soil disturbance and crop residue retention should be a good option for its multiple positive externalities including SOC accumulation and better yield.

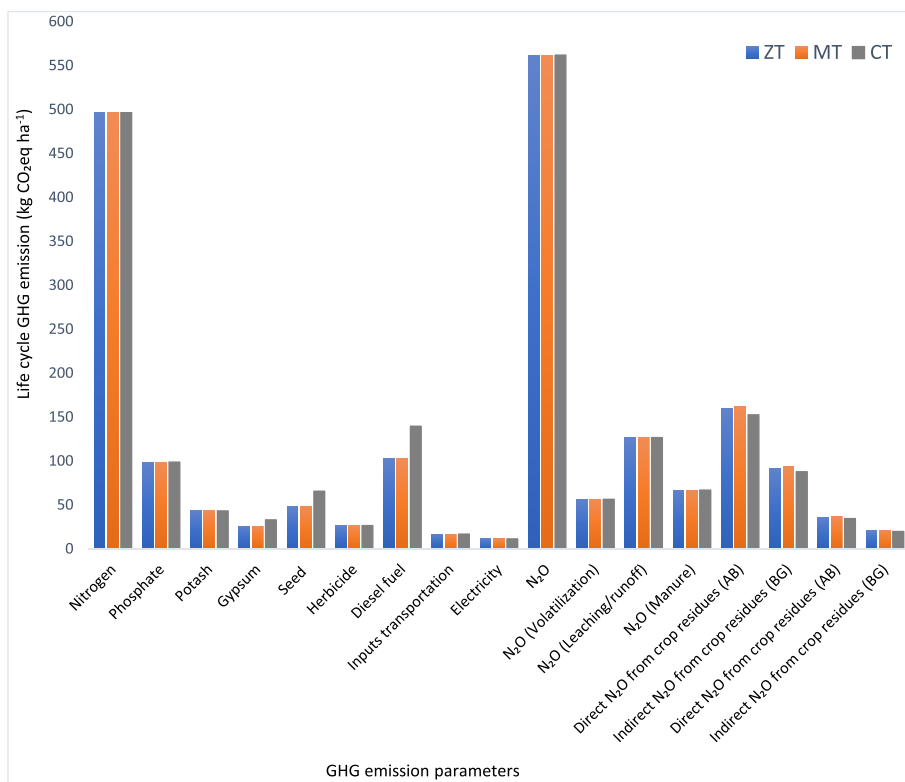


Fig. 5. GHG emission from inputs in kg CO<sub>2</sub>eq ha<sup>-1</sup> in wheat cultivation. ZT = Zero tillage; MT = Minimum tillage; CT=Conventional tillage practice; AB = Above ground; BG = Below ground.

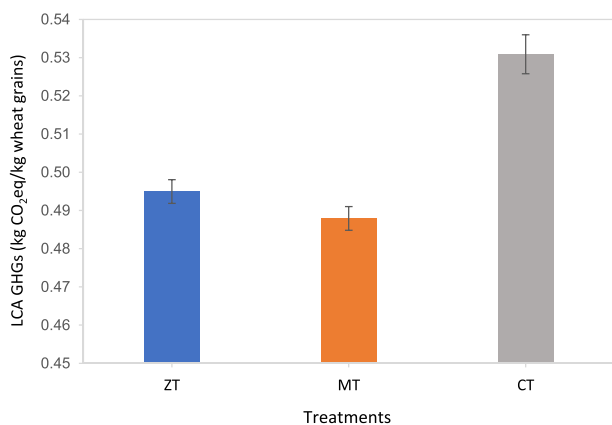


Fig. 6. Life cycle GHG emission within life cycle assessment (LCA) approach for wheat production ( $p < 0.05$ ).

### 3.4. Conservation tillage impact on GHG emission

As an indicator of environmental sustainability, GHG emission reduction forms one of the three primary goals of climate-smart agriculture, while also serves as the environmental impact reduction objective of sustainable intensification. GHG emission for different tillage treatments was estimated to evaluate their climate change mitigation potential. Total GHG emission was estimated at 1987 kg CO<sub>2</sub>eq ha<sup>-1</sup>, 1992 kg CO<sub>2</sub>eq ha<sup>-1</sup> and 2028 kg CO<sub>2</sub>eq ha<sup>-1</sup> for ZT, MT and CT practices, respectively; CTS with residue retention was found to significantly reduce GHG emission in wheat cultivation. Fig. 5 and Fig. 6 presents the total life cycle GHG emission for inputs use in wheat crop production. ZT practice with crop residue retained (20 cm) had the greatest climate change mitigation potential with respect to GHG emissions, followed by MT practice with crop residue retention. Nonetheless, CT practice is the most commonly practiced tillage by farmers in Bangladesh and it was

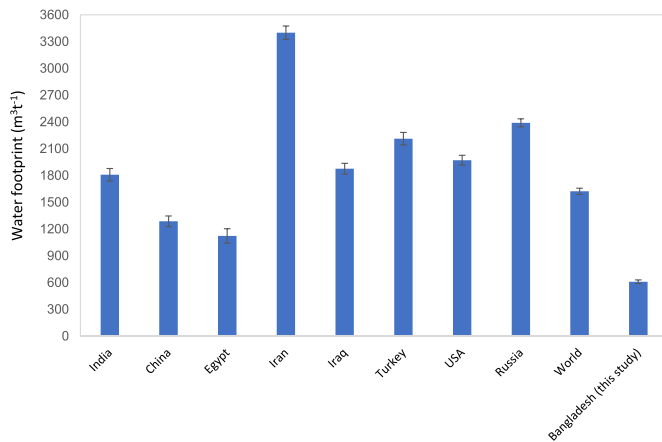
found to emit the highest among the three options experimented. The major share of the total amount of GHG emission in wheat cultivation came from Nitrous oxide (N<sub>2</sub>O). The average N<sub>2</sub>O emissions were about 562 kg CO<sub>2</sub>eq ha<sup>-1</sup> in wheat, with shares of 28.28%, 28.21% and 27.71% of total GHG emission for ZT, MT and CT practice, respectively. Then nitrogen (N) fertilizer was found to be the second largest contributor of 24.98%, 24.92% and 24.47% of emissions for ZT, MT and CT practices respectively, followed by N<sub>2</sub>O from aboveground crop residues, nitrous oxide leaching/runoff, diesel fuel, phosphatic fertilizer, N<sub>2</sub>O from belowground crop residues, N<sub>2</sub>O from manure, N<sub>2</sub>O volatilization, seed, potash, herbicide, transportation of inputs and electricity. N fertilizer and N<sub>2</sub>O are the main sources of GHG emission, while parts of the N fertilizer was dissolved aboveground in the form of ammonia (NH<sub>3</sub>) volatilization and remaining parts of the nitrogen applied to soil converted to N<sub>2</sub>O naturally by denitrifying soil microbes. The total GHG emissions will not give us the full picture until the SOC accumulation is not taken into account, and which gives the net GHG emission. The estimated NGHG were 1982 kg CO<sub>2</sub>eq ha<sup>-1</sup>, 1988 kg CO<sub>2</sub>eq ha<sup>-1</sup>, and 2028 kg CO<sub>2</sub>eq ha<sup>-1</sup> for ZT, MT and CT practice, respectively (Table 6). A recent study carried out in Pakistan reported much lower GHG emissions from the cultivation of various crops such as potato (993 kg CO<sub>2</sub>eq ha<sup>-1</sup>), transplanted rice (1100 kg CO<sub>2</sub>eq ha<sup>-1</sup>) and wheat (1118 kg CO<sub>2</sub>eq ha<sup>-1</sup>) (Imran et al., 2020). By contrast, in China, GHGs produced from wheat cultivation were almost two times of that we found in this study (5455 kg CO<sub>2</sub>eq ha<sup>-1</sup>) (Zhang et al., 2017), which can be mainly attributed to the heterogeneous application of N fertilizers and frequency of tillage practices.

### 3.5. Conservation tillage impact on carbon footprint

GHG intensity or carbon footprint (CF) is represented as (1) life cycle CF, and (2) Net life cycle CF. Table 6 presents the Results of the net life cycle CF for wheat production. The life cycle GHG intensity or CF was estimated at 0.495 kg CO<sub>2</sub>eq kg<sup>-1</sup>, 0.488 kg CO<sub>2</sub>eq kg<sup>-1</sup> and 0.531 kg CO<sub>2</sub>eq kg<sup>-1</sup> of wheat grains for ZT, MT and CT practices, respectively.

**Table 7**  
Water use efficiency and water footprint under different tillage practices.

Treatment	No. of Irrigation	Irrigation Water (m <sup>3</sup> )			Effective rainfall (m <sup>3</sup> )	Total Water amount (m <sup>3</sup> )	Wheat Yield (t ha <sup>-1</sup> )	Water use efficiency (t m <sup>-3</sup> ha <sup>-1</sup> )	Water Footprint (m <sup>3</sup> t <sup>-1</sup> )
		DAS at 2	DAS at 25	DAS at 51					
ZT (T <sub>1</sub> )	3	225	1100	1000	0	2325.8	4.02	0.0017	578.56
MT (T <sub>2</sub> )	3	225	1100	1000	0	2325.8	4.08	0.0018	570.05
CT (T <sub>3</sub> )	3	225	1100	1000	0	2325.8	3.82	0.0016	608.85



**Fig. 7.** Comparison of water footprint in wheat cultivation: this study versus data from select regions of the world based on the ref (Ewaid et al., 2019).

The estimates are based on single impact global warming index (GWI) of wheat cropping by accounting life cycle assessment (LCA) of the crop system boundary. To avoid potential omission bias, the estimation of net life cycle carbon footprint (CF), must consider SOC accumulation in addition to inputs use. So, the net life cycle GHG intensity or carbon footprint (CF) was estimated as 0.493 kg CO<sub>2</sub>eq kg<sup>-1</sup>, 0.487 kg CO<sub>2</sub>eq kg<sup>-1</sup> and 0.531 kg CO<sub>2</sub>eq kg<sup>-1</sup> of wheat grain for ZT, MT and CT practices respectively. It is estimated that per kg of wheat grain production emitted 0.495 kg CO<sub>2</sub>eq kg<sup>-1</sup>, 0.488 kg CO<sub>2</sub>eq kg<sup>-1</sup> and 0.531 kg CO<sub>2</sub>eq kg<sup>-1</sup> for ZT, MT and CT practices, respectively. Previous studies reported CFs of 0.377 kg CO<sub>2</sub>eq kg<sup>-1</sup>, 0.343 kg CO<sub>2</sub>eq kg<sup>-1</sup> and 1.31 kg CO<sub>2</sub>eq kg<sup>-1</sup> of wheat grain (Gan et al., 2012; Gan et al., 2014) (Wang et al., 2021). The wide range of emission intensities (CF) observed under various studies could be attributed to the nature and kind of tillage and inputs consumed. A lower GHG intensity is observed where the N fertilizer consumption is low or CT practice are adopted or where CT is practiced in combination with low N fertilizer consumption.

The studies reported that CA-based CTS and crop residue retention increases SOC in the topsoil (Naresh et al., 2013), and the SOC could be increased by crop residues retention, minimal soil disturbance and crop rotation with legume crops (Alam et al., 2018; Baldock, 2007). SOC accumulation was found to significantly reduce net life cycle CF ( $p < 0.05$ ). Results also revealed that CTS practices such as ZT and MT practice compared to CT practice were very effective in reducing lifecycle CF because their entire plough profile remained undisturbed throughout the wheat growing period.

### 3.6. Conservation tillage impact on water footprint

Water footprint (WF) is the total amount of water used to produce a certain food from 1.0 ha of land and it is usually denoted by cubic meter per hectare. Table 7 shows water use efficiency (WUE) and WF Results for different tillage treatments. The assessment of water consumption during the whole lifecycle of crop growing period is required to calculate the WF and water productivity. Water footprint estimated from this experiment were 578.56 m<sup>3</sup> t<sup>-1</sup>, 570.05 m<sup>3</sup> t<sup>-1</sup> and 608.85 m<sup>3</sup> t<sup>-1</sup> for ZT, MT and CT

practices, respectively.

Water use efficiency (WUE) or water productivity was found to be 0.0017 t ha<sup>-1</sup> m<sup>-3</sup>, 0.0018 t ha<sup>-1</sup> m<sup>-3</sup> and 0.0016 t ha<sup>-1</sup> m<sup>-3</sup> for ZT, MT and CT practices, respectively. The CA tillage practices are designed to optimize the use of water carefully in water deficit wheat cultivation environments (Sayed et al., 2020; Sultan et al., 2017). In water limited environments, a comparison of water consumption for wheat production for different regions of the globe are illustrated in Fig. 7. It is clear from the table that less water is needed for wheat production in Bangladesh in comparison to other regions. Nonetheless, the major share of water consumed by wheat cropping in Bangladesh came from irrigation using blue water, which in turn will increase crop production cost. So it was important to investigate the WF of different tillage options to advise farmers on reducing the production cost. More importantly, under the risks of climate change with increasing incidents of prolonged drought and storm events, no-till management will play an important role in provision of increased infiltration, reduced surface water loss by runoff and increased plant available water (Liu and Basso, 2020). Alongside CA dissemination, in-season advisory system for irrigation water management, taking into account of actual weather conditions and forecasts, could be a useful tool for farmers (Schulthess et al., 2019).

## 4. Conclusion

Agriculture is both the source and victim of climate change. While climate change exerts adverse effects on crop production and farmer livelihoods, intensive soil tillage and undesirable input management would hasten the climate change process through GHG emissions. Bangladesh targets to reduce 15 percent of its annual greenhouse gas emissions arising from agriculture and livestock through the development of a climate smart agriculture investment plan. Reducing GHG emissions and water footprint (WF) as well as increasing soil organic carbon (SOC) are considered as effective measures to achieve high crop productivity with minimum environmental impact. Conservation agriculture (CA) based conservation tillage systems (CTS) with crop residue retention is often suggested as a cost-effective cum resources conserving alternative to increase crop productivity without compromising soil health and environmental sustainability of cereal cropping systems. This experiment in wheat crop showed that conservation tillage with crop residue retention increased soil organic carbon accumulation rate and intensity compared to conventional tillage that employs several numbers of intensive soil inversion tillage. Results further indicated that conservation tillage sequestered approximately 10 times of soil carbon than conventional tillage. While the Net lifecycle GHG emissions were highest in conventional tillage without crop residue retention, minimum tillage (MT) practice had the lowest carbon and water footprint amid all the tillage options studied. These results indicated that in relation to the conventional management of wheat with inversion tillage and residue removal, CTS including MT and ZT practice both with crop residue retention are potential climate change mitigation and adaptation strategies suitable for agricultural production systems of Bangladesh. Nonetheless agronomic interventions alone are not sufficient to disseminate the adoption of climate smart conservation tillage in Bangladesh; rather, comprehensive and integrated development programs including extension, credit, and asphalted roads are required to assist in the adoption of these sustainable crop management practices.



## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.indic.2021.100106>.

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