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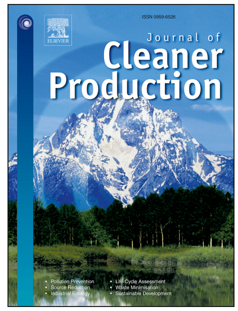

Greenhouse Gas Implications of Novel and Conventional Rice Production Technologies in the Eastern–Gangetic Plains

Md. Khairul Alam, Wahidul K. Biswas, Richard W. Bell

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Authors: Md. Khairul Alam[a]; Wahidul K. Biswas[b]; Richard W. Bell[a]

Corresponding Author: Md. Khairul Alam

Corresponding Author's affiliation: Land Management Group, School of Veterinary and Life Sciences, Murdoch University, WA 6150, Australia; e-mail: khairul.krishi@gmail.com

First Author's name and address: Md. Khairul Alam, Land Management Group, School of Veterinary and Life Sciences, Murdoch University, WA 6150, Australia; e-mail: khairul.krishi@gmail.com

[a]Land Management Group, School of Veterinary and Life Sciences, Murdoch University, WA 6150, Australia; e-mail: khairul.krishi@gmail.com

[a]Land Management Group, School of Veterinary and Life Sciences, Murdoch University, WA 6150, Australia; R.Bell@murdoch.edu.au

[b]Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Bentley, Western Australia 6845, Australia; e-mail. W.Biswas@curtin.edu.au

Greenhouse Gas Implications of Novel and Conventional Rice Production Technologies in the Eastern–Gangetic Plains

Abstract

Wetland rice (*Oryza sativa* L.) production contributes 55% of agricultural greenhouse gas (GHG) emissions in the world. Hence any new technology with the potential to reduce the GHG emissions of wetland rice could make a significant contribution to total global warming mitigation by agriculture. We applied a streamlined life cycle assessment to the effect of a novel unpuddled transplanting of rice and of increased crop residue retention on GHG emissions from rice fields in the Eastern Gangetic Plains. We compared them with the conventional puddling of soils and current residue retention for transplanting. The GHG emissions from one tonne of rice production for the following four cropping practices were studied: a) conventional puddled transplanting with low residue retention (CTLR); b) conventional puddled transplanting with high residue retention (CTHR); c) unpuddled transplanting following strip tillage with low residue retention (UTLR) and; d) unpuddled transplanting with high residue retention (UTHR). The emissions recorded on–farm and emissions related to pre–farm activities were converted to CO_2–eq using Global Warming Potential (GWP) values of GHGs for 20-, 100- and 500-year time horizons. The GHG emissions of 1 tonne of rice varied from 1.11 to 1.57 tonne CO_2–eq in the 100-year horizon. For all four treatments, soil methane (CH_4) was the predominant GHG emitted (comprising 60–67% of the total) followed by emission from on–farm machinery use. The UTLR was the most effective GHG mitigation option (it avoided 29%, 16% and 6% of the total GHG emissions in comparison with CTHR, CTLR and UTHR, respectively) in wetland rice production. The novel minimum tillage establishment approach for rice involving strip tillage followed by UT has potential to increase global warming mitigation of wetland rice in the Eastern Gangetic Plains, but further research is needed to assess the role of increased residue retention.

Key words: Barind area, global warming mitigation potential, labour requirement, life cycle assessment, puddling, rice based cropping systems, unpuddled transplanting

Correspondence: Md. Khairul Alam; khairul.krishi@gmail.com; +6170114336/+8801815029112

Abbreviations:

ACIAR–Australian Centre for International Agricultural Research
ADB–Asian Development Bank
BARC–Bangladesh Agricultural Research Council
BBS–Bangladesh Bureau of Statistics
BDT–Bangladeshi taka
CA–Conservation agriculture
C–Carbon
CH_4–Methane
CO_2–Carbon dioxide
CO_2eq–Carbon dioxide equivalent
DECC–Department of Energy and Climate Change
DEFRA–Department for Environment, Food and Rural Affairs
FPMU–Food Planning and Monitoring Unit
GC–Gas chromatograph
GHG–Greenhouse gas
GoB–Government of Bangladesh
GWP–Global Warming Potential
IEA–International Energy Agency
IFA–International Fertilizers Association
IGP–Indo–Gangetic Plains
IPCC–Inter–Governmental Panel on Climate Change
ISO–International Organization of Standardization
LCA–Life Cycle Assessment
LCI–Life Cycle Inventory
LSD–Least significant difference
MoP–Muriate of potash
N_2O–Nitrous Oxide
NO_3^-–Nitrate ion
NO–Nitric Oxide
NPP–Net primary production
OM–Organic matter
Rh–Redox potential
SPSS–Statistical Package for the Social Sciences
SRI–System of Rice Intensification
TPR–Puddled transplanted rice
UN-FCCC–United Nations Framework Convention on Climate Change
UT–Unpuddled transplanting of rice
US$–United States Dollar
USA–United States of America

1. Introduction

Wetland rice (*Oryza sativa* L.) production is a major contributor to the worldwide budget of GHGs from agriculture (IPCC, 2013). Many of the factors controlling gas exchange between rice paddies and the atmosphere are different from those in upland agriculture because rice fields are flooded during most of their cultivation period (Saito et al., 2005; Miyata et al., 2000). Novel establishment technologies are being developed for rice mostly to cope with the decreased availability of labour and water (Islam et al., 2010 and 2013). A novel solution to these constraints for rice production is unpuddled transplanting (UT), a technique of transplanting rice seedlings after minimal soil disturbance in contrast to the conventional practice that puddles soil following several wet tillage operations (Malik et al., 2009). Beside reduced labour and fuel costs and improved timeliness in crop establishment, initial research suggests that UT reduces water requirements for rice establishment. However, it remains unclear how UT of rice cultivation alters CO_2, CH_4 and N_2O emissions and overall global warming potential (GWP).

As a major contributor to global food supply, the rice–wheat cropping system in the Indo–Gangetic Plains (IGP) of South Asia area currently covers about 13.5 Mha of land in Pakistan, Nepal, India, and Bangladesh (Gupta and Seth, 2007). Emission of GHG from rice fields is very sensitive to crop establishment techniques and management practices (Wassmann et al., 2004). The conventional puddled transplanted rice (CT) is a major source of GHG emission, particularly methane (Pathak et al., 2011). Puddling is done to facilitate transplanting of seedlings, suppress weeds and to reduce water loss by percolation. The saturated soil condition lowers soil oxygen content and also soil redox potential, which increases the activity of methanogens (Sharma and DeDatta, 1985) that determine production of CH_4 in the soil. Other soil microbial processes controlling denitrification are regulated largely by oxygen status in the soil, which in turn is dependent on soil water content (Nishimura et al., 2004). No–tillage reduced CH_4 emissions because rice straw was retained on the soil surface and the soils under those conditions were more oxidised than those of CT (Ito et al., 1995). Dry direct–seeded rice (DSR) decreased CH_4 emission as DSR fields were not continuously submerged with water (Ko and Kang, 2000; Pathak et al., 2012b). Corton et al. (2000) and Pathak et al. (2012a) predicted that the GWP can be reduced by 16 to 33 % if the entire area of the Indo–Gangetic Plains under CT was converted to DSR in a rice–based cropping system. The net effect of direct seeding on GHG emissions also depends on N_2O emissions, which increase under aerobic conditions. For example, N_2O emissions were 1.5 times greater in SRI

(System of Rice Intensification) studies due to the increased soil aeration (Peng et al., 2011; Hou et al., 2012). Wassmann et al. (2004) found that measures to reduce CH_4 emissions often lead to increases in N_2O emissions, and this trade–off between CH_4 and N_2O is a major hurdle in reducing GWP of wetland rice. Ideal strategies would reduce emissions of both CH_4 and N_2O simultaneously. The recent development of UT of rice together with residue retention using bed planting, or strip tillage, as a form of conservation agriculture (CA) for rice establishment (Malik et al., 2009), need to be assessed in terms of relative effects on emissions of CH_4 and N_2O and on GWP mitigation.

Life cycle assessment (LCA) is an approach to quantify the carbon footprint of a production process, and to identify hotspots and steps in the process where greatest climate change mitigation can be achieved. Although there are difficulties in applying LCA in agriculture, progress has been made with incorporation of on–farm emission of grain production into pre–farm and post–farm value chains of products so that a complete carbon footprint of agricultural processes from production to consumption can be calculated (Blengini and Busto, 2009; Meisterling et al., 2009).

Equivalent CO_2 emissions per unit of conventional wetland puddled rice production have been measured previously (Hayashi and Itsubo, 2005; Koga et al., 2006; Masuda, 2006). The activities that drive the emission factors include fertilizer production and distribution, agricultural chemical production and distribution, machinery manufacturing and use and irrigation application (Architectural Institute of Japan, 2003). Kasmaprapruet et al. (2009) have reported that during the life–cycle of rice, most (95%) GWP is contributed by the cultivation, followed by harvesting (2%) and seeding and milling processes (2%). In Italy, LCA has shown that the environmental benefits per tonne are greatly reduced in the case of upland rice production, due to low rice grain yields (Blengini and Busto, 2009). Farag et al. (2013) in their LCA study showed that CH_4 emission from the flooded rice fields was the main source of GHG emissions, contributing about 53%, while N fertilization added about 10% and mechanical activities about 1% of the total emissions. On the other hand, in most arable agriculture, as shown by Woods et al. (2008), N_2O is the dominant GHG, being responsible for 80% of wheat GHG emissions. Eshun et al. (2013) in a LCA revealed that

N_2O contributed the highest proportion (about 70%) of GWP for paddy rice production, followed by CO_2. The LCA conducted by Yoshikawa et al. (2010) found that the differences in emission are mainly due to field CH_4 in rice production. Harada et al. (2007) compared conventional puddling with no–tillage rice through a LCA study including pre-farm and on-farm stages where no-till rice had 43% lower cumulative CH_4 emission and the potential to save 1.78 tonne CO_2 ha^{-1} relative to puddled rice.

Incorporation of CA in the rice–based triple cropping system in the Eastern Gangetic Plains remains challenge. The recently developed UT of rice, which involves minimum tillage planting, is suitable for CA and has performed well in yield (Haque et al., 2014), financial returns, soil quality (Sharma et al., 2008) and fuel consumption (2 to 3 times lower) (Islam et al., 2013), but has not been examined for its effects on GWP. Moreover, the effects of residue retention level under UT of rice also need to be assessed. A LCA analysis of the new UT rice production technology can estimate its potential contribution to GWP (Haas et al., 2001; Schmidt, 2008; Blengini and Busto, 2009; Meisterling et al., 2009). The present study was carried out to:

1. assess the GHG emissions for conventional puddling and UT with different levels of crop residue retention;
2. determine the hotspots contributing significantly to the GHG emissions within the system boundaries by a LCA study, and
3. identify the causes for the predominant GHG emissions during the pre– and on–farm stages of rice production.

2. Materials and methods

2.1. Study site and experimental design

The effects of changing from conventional soil puddling to UT along with two levels of residue retention was investigated in Northwest Bangladesh at Alipur village, Durgapur upazilla, Rajshahi division in an Agro–ecological Zone known as the Level Barind Tract (LBT). This region has a distinct physiography of terraced lands at about 8 m above sea level. The region is characterized by low annual rainfall (1370 ± 323mm) with uneven rainfall distribution and wide variation from year to year and high temperature range (maximum 42.9^{o}C in June 2014 and minimum 6.2^{o}C in January, 2014). The texture class of the experimental soil was silt loam (44% sand, 34% silt and 22% clay) and the bulk density ranged from 1.38 g cm^{-3} in strip tillage with high residue retention to 1.49 g cm^{-3} in conventional tillage with low residue retention. The clay minerals of the soils are mostly mica, kaolinite, interstratified mica–vermiculite–smectite and kaolinite–smectite (Moslehuddin et al., 2009). The soil was slightly acidic and classed as Calcareous Brown Flood Plain and Calcareous Dark Grey Floodplain soils (Aeric Eutrochrept). The field site was moderately drainable as it was located above the flood level (BARC, 2005).

The field study in 2014 examined two tillage practices (CT and UT) and two residue retention levels (high residue retention–HR and low residue retention–LR) from four replicates of the treatments in an experiment established in 2010 (Islam et al., 2013). The experimental design, followed for the previous 11 crops (three crops per year since 2010), used a split-plot layout where tillage practices were assigned to the main plots and residue retention levels to the subplots. Low residue approximates current farmer practice for this region which involves keeping about 20% of the standing rice crop residue in the field during harvesting of crops. High residue retained 50% of standing rice residue after harvesting. For the previous lentil, mungbean and mustard crops in the rotation, LR involved complete removal while HR returned all crop residues to the plot. The cropping sequence followed for the first three years in the field was lentil (*Lens culinaris* L.) –mungbean (*Vigna mungo* L.) – rain–fed monsoon rice. In 2013–14, the monsoon rice was followed by mustard (*Brassica campestris* L.) and then irrigated dry season rice. Additional chemical inputs were recorded, and were typical of local farming practices. Soil GHG emissions (CO_2, N_2O and CH_4) were measured repeatedly at 1–week intervals from each plot throughout the study period using a closed chamber system. During application of split N fertilizer doses and during drying and re–wetting of the field, the measurement was more frequent (once in two- or three- day interval).

Close Chamber method

Transparent chambers (30 cm length × 30 cm width × 60 cm height) were made with 3 mm thick acrylic sheets for microbial respiration (Rm) measurement in the field (Hutchinson and Livingston, 1993). Each chamber was covered by dark sheet during Rm measurement. Every sampling event was replicated three times. Immediately after transplanting of rice, selected seedlings were removed so that an aluminium chamber base of 31 cm length × 31 cm width × 7 cm height), complete with a 1 cm × 2.5 cm (width × deep) water groove on the inner side, could be placed on the bare space. The base of the chamber was inserted to 7 cm depth in the soil and the groove was filled with water to make the system air–tight when the measurement was done. Samples were collected within 10:00–16:00 on every sampling day. For the initial gas sample, a silicon tube was attached to the top of the chamber, and a 50 ml gas–tight polypropylene syringe was used at 0 minute after setting up of chamber to extract the gas. The second sampling was done after a further one hour. When an higher amount of gas was required, a 400 ml Tedlar bag was filled up through a silicon tube connected to the syringe.

For CH_4 and N_2O measurements in the fields, transparent gas chambers of 60 cm length × 30 cm width × 100 cm height made by 5 mm thick acrylic sheets were placed over four plants. To allow pressure adjustments in the chamber during gas sampling, a plastic light weight bag was fixed inside. A digital electronic thermometer was attached inside the chamber within a silicon cork. Samples were collected within 10:00–16:00 on every sampling day but timing of sampling days varied according to need and life cycle analysis. Samples were collected in a 50 ml polypropylene syringe at 0 and 60 minutes after sealing the chamber. For sampling of N_2O, a longer time interval was, sometimes, used before collecting the second sampling. The syringe was made air–tight with a three–way stopcock and gas was transferred into a 35 ml bottle and when required transferred into a 400 ml Tedlar bag through a silicon tube attached to the top of the chamber. The gas samples were analysed using gas chromatography for CO_2, CH_4 and N_2O with a CO_2 detector, hydrogen flame ionized detector and combined gas analyzer, respectively (Naser, 2005).

Gas flux calculations

Gas flux was calculated using the following equation (Yagi et al., 1991):

$$F = V/A \times \Delta c/\Delta t \times 273/T \times \rho \text{———} (1)$$

F is the gas flux (mg m^{-2} h^{-1}), V (m^3) and A (m^2) are volume and bottom area of the chamber, respectively; $\Delta c/\Delta t$ (10^{-6} m^3 m^{-3} h^{-1}) is the gas concentration change in the chamber during a given period;

T is the absolute temperature (K); ρ is the density of gas at the standard condition (CO_2 =1.96 kg m^{-3}, CH_4 = 0.716 kg m^{-3} and N_2O = 1.97 kg m^{-3}); and

With the assumption that GHG emissions follow a linear trend during the interval when gas sampling was not done, total gas fluxes for the rice growing season were calculated by the successive linear interpolation of average gas emissions on the sampling days:

$$\text{Cumulative gas emission} = \sum_{i=1}^{n-1}(R_i \times D_i) \text{————} (2)$$

Where, R_i is the mean gas flux (mg m^{-2} d^{-1}) of the two sampling times; D_i is the number of days in the sampling interval, and n is the number of sampling times.

2.2. Streamlined LCA assessment of GHG emissions from field paddy production

The streamlined LCA approach was adopted; LCA analysis only considered cradle–to–farm gate GHG emissions (Todd and Curran, 1999; Denham et al., 2014). In addition, this research considered GHG emissions only for estimating GWP, which is categorized as a limited impact, focused LCA analysis (Finkbeiner et al., 2011; Barton et al., 2014). This streamlined LCA followed the four steps of ISO 14040–44 to estimate the GHG emissions, including goal, scope, life cycle inventory, impact assessment and interpretation. The interpretation was reported in the results and discussions section.

2.2.1. Goal and scope

Greenhouse gas emissions from rice production were calculated for the following farming practices:

I. Conventional puddled transplanting with low residue retention (CTLR)

II. Conventional puddled transplanting with high residue retention (CTHR)

III. Unpuddled transplanting with low residue retention (UTLR)

IV. Unpuddled transplanting with high residue retention (UTHR)

The goal was accomplished with a functional unit which is the production of one tonne of paddy rice grain. The system boundary consists of pre–farm and on–farm life cycle stages. The input and output data of these life cycle stages for producing one tonne of rice are then quantified to form life cycle inventories for CT and UT with LR and HR retention. The GHG emissions from pre–farm stage involve the multiplication of the amount of inputs with their corresponding emission factors to determine the GHG emissions associated with the production and transportation of these inputs to a paddy field. On–farm GHG emissions are outputs resulting from farm machinery operation and chemical applications. The GHG emissions from pre–farm and on–farm stages are added to determine the amount of GHG emissions associated with the production of one tonne of rice (Figure 1). The inclusion of soil–carbon sequestration associated with rice production in this carbon accounting is beyond the scope of the paper.

2.2.2. Life cycle inventory

Life Cycle Inventory that consists of inputs (e.g., fertilizers, machinery, fungicides, insecticides, herbicides) and outputs (CO_2, CH_4 and N_2O) of pre–farm and on–farm stages (Table 1) of rice production is a pre–requisite to estimate total life cycle GHG emissions.

Pre–farm emissions

Pre–farm GHG emissions include the emissions associated with all activities for producing farm inputs, including chemicals, energy and machinery and the emissions from the transportation of inputs to the paddy field.

Chemicals–The GHG emissions from the production of chemicals were calculated so that the emission factors reflect the situation in Northwest Bangladesh. However, in the absence of the local emission factors of inputs applied to Bangladesh agriculture, a mix of generic and local data were utilized to develop emission factors for calculating the GHG emissions from the production and transportation of inputs. The generic value of embodied energy consumption that is associated with energy consumption in all stages of the production of an input was sourced from recognized literature (RMIT, 2007; DEFRA, 2008; Bosch and Kuenen, 2009; Brander et al., 2011), which was multiplied by the local emission factor for energy production (ADB, 1994; GoB, 2011; Brander et al., 2011).

In some cases, the data for calculating emission factors of chemicals, e.g. insecticides Malathion™ (malathion: 0,0 dimethyl phosphorodithioate of diethyl mercaptosuccinate), Sumithion™ (fenitrothion), fungicides Amistar™ (azoxystrobin) and Tilt™ (propiconazole) and herbicide Refit™ (pretilachlor), were unavailable in the existing literature and so, a local database was assembled by contacting the local manufacturers directly. The commercial databases of the products were also checked to quantify the energy used for the production of a unit. The information on energy consumption was obtained from Syngenta Bangladesh, Shetu Corporation Bangladesh, and Bangladesh fertilizer companies (Quader, 2003; BBS, 2013) (Karnaphuli Fertilizer Company/Ghorasal Fertilizer Company/Fenchugonj Natural Gas Fertilizer Company/Chittagong Urea Fertilizer Company/Jamuna Fertilizer Company/Polash Urea Fertilizer company) for determining the GHG emission factors of urea, superphosphate and pesticide production. Considering CO_2, CH_4 and N_2O emissions along with transportation and distribution losses for the generation of electricity for all types of mixes of fuel (gas/oil/coal), the emission factor used for the study is 0.64 kg CO_2–eq/kWh (Brander et al., 2011).

In the case of inputs imported to Bangladesh, the GHG emissions from their manufacture overseas and their transportation to paddy fields were calculated. Bangladesh imports urea, gypsum, muriate of potash (MoP) fertilizers from Belarus, triple superphosphate (TSP) from Morocco and Zn and B from China (Bangladesh Business News, 2013; BBS, 2013). Since no literature provided the emission factors of these fertilizers, generic values of energy consumption of urea, TSP, MoP, S, Zn and B fertilizers production were multiplied with the emission factors of energy production of the source countries of the fertilizers. The energy consumption for unit mass of fertilizer component production was collected from European and Asian (China) literature (Brentrup and Pallière, 2008, DEFRA, 2008; Zwiers et al., 2009; Bosch and Kuenen, 2009) and then they were multiplied by the emission factors of energy production of Belarus, Morocco, Tunisia, and China, which were sourced from IFA (2009) and IEA (2007 and 2012).

Farm machinery–The GHG emissions from the manufacture of farm machinery were estimated using the USA input/output database (Suh, 2004), based on the monetary value of the machinery, with allowances for exchange rates and inflation (Biswas et al., 2008; Barton et al., 2014). The USA input/output database contains environmental emission data for the manufacture of US$1 equivalent farm machinery. The present value of farm machinery in BDT was converted to the price of 1998 at a deflation rate of 6.64% per year which, eventually, was converted to 1998 US$ with a 0.022 multiplier (WB, 2014; XE.com, 2014). After determining the machinery cost in line with 1998 US$ for one tonne of rice production, it was multiplied by the GHG emission factor of machinery manufacturing (0.15 kg CO_2–eq/US$).

Transport–The GHGs from the transport of inputs to the rice field were calculated according to the LCA database (INFRAS, 2010; Kitzes, 2013; HBEFA, 2014; World Resource Institute and WBCSD, 2013). A variety of transport modes including shipping, and trucks (3–7 tonnes) were used to transport inputs from factory gate to the farm and were recorded in tonne–kilometres. When inputs were transported by sea on an ocean–going freighter, a sole sea passage from the port nearest to the manufacturer and to the user were calculated following Biswas et al. (2008) and Barton et al. (2014).

On–farm emissions

On–farm data comprised emissions from farm machinery operations, including cultivation, irrigation and harvesting, and from soil emissions.

Farm machinery–Fuel consumed by farm machinery per hectare was recorded during farming operations in the field experiment. The GHG emissions during the farm machinery operations were calculated by applying the emission factor of fuel for light machinery use (RMIT, 2007; INFRAS, 2010; HBEFA, 2014). Machinery usage was expressed as the amount of fuel in litres per hectare in terms of standard machinery for the region (L t^{-1}). Fuel consumption was dependent on land area, machinery width and the number of times the machinery passed across the land.

Soil –The direct emissions of CO_2, CH_4 and N_2O from soil were quantified at the experimental site (as described above), but the indirect N_2O emissions through ammonia volatilization and leaching were ignored due to soil properties which made these losses unlikely to be significant (IPCC, 2006). Nitrogen use efficiency was expected to be high due to well-controlled continuous flooding of soil to minimize N loss through leaching and volatilization (Bandyopadhyay et al., 2009). Previous measurements of soil strength at this site (M. A. Islam, personal communication) indicate the presence of a plough-pan that would prolong urea residence time in soil resulting in restricted N leaching to deeper soil layers (Patil and Das, 2013). Little of the fertilizer-derived NH_4^+-N would be oxidized biologically to NO_3-N under the prevailing anaerobic soil conditions which would lower the risk of NO_3-N leaching and N_2O production due to denitrification (Savant and de Datta, 1982). These rice soils also contain clay minerals such as illite or vermiculite (Moslehuddin et al., 2009) which immobilise NH_4^+-N through fixation (Allison et al., 1953) leading to low rates of NH_3 volatilisation.

2.2.3. Impact assessment

Impact values of global warming are expressed over 20-, 100- and 500-year time horizons to enable policy makers to make relevant climate change decisions. Accordingly, individual greenhouse gas (CO_2, CH_4 and N_2O) emissions from each production stage were converted to CO_2–eq using established conversion factors for 20-, 100- and 500-year time horizons (IPCC, 2013). But we only discuss 100 year horizon as it is considered as the reference for climate change policy (UN-FCC, 1992 and Fearnside, 2002). Greenhouse gas emissions (as CO_2–eq) were then calculated on a per tonne of rice basis. The seasonal CO_2–eq per hectare (kg CO_2–eq ha^{-1} $season^{-1}$) was calculated by summing CO_2–eq across the season. Total GHG emissions per tonne of rice (kg CO_2–eq per tonne rice) were calculated for the single rice season (from late February to June).

2.3. Statistical analysis

The effects of UT and residue retention on CO_2–eq emission for the two stages within the rice production system boundary were assessed using a two–factor analysis of variance. All data were statistically analyzed with SPSS (Statistical Package for the Social Sciences) software package version 21 (SPSS Inc., Chicago, IL, USA). Means were compared by using least significant difference (LSD) at $p< 0.05$. The statistical analyses of CO_2–eq emission per tonne of rice production only for on–farm CO_2, CH_4 and N_2O emissions were conducted since the use of inputs (i.e. energy, chemicals, and machinery) did not vary among treatments.

3. Results and discussion

3.1. Implications of minimum tillage and increased residue retention for streamlined life cycle GHG emissions during wetland rice production

The GHG emissions of rice production were influenced ($p<0.05$) by crop establishment and residue management techniques (Figure 2). Among the techniques, the total GHG emissions from 1 tonne of rice production followed the ascending order: CTHR<UTHR<CTLR<UTLT. Overall, UT (UTLR and UTHR) offers greater GHG saving in the 100-year time horizon (29%, 24% over CTHR and 18%, 16% over CTLR) relative to the conventional puddling method. More specifically, UTLR had the highest reduction potential for on–farm emissions due to emission of least CH_4. Although the yield in UTHR was higher than that in UTLR, the latter performed better in terms of total GHG emissions per tonne of rice mainly because the CH_4 emissions (25 times more warming potential in 100-year time horizon than CO_2) from the high residue retention outweighed the benefits associated with the increased yield.

The lowest emissions by UTLR can be attributed to less disturbance of soil and the presence of a thin oxidised layer at the soil–water interface which may ensure the ongoing flow of oxygen to the soil (Ponnamperuma, 1972). This may favour the activity of CH_4 oxidizing bacteria which would diminish soil CH_4 emissions (le Mer and Roger, 2001). Anaerobic conditions develop within saturated rice soils within hours of flooding (Adhya et al., 2000; Bodelier, 2003) favouring the growth of methanogens that produce CH_4 as a by–product of their respiration. The application of carbon sources like straw that stimulate methanogen survival and the low redox potential are both driving factors for CH_4 emission (Wang et al., 2000; Yao et al., 1999).

The UTLR and UTHR were statistically similar in terms of on–farm emissions of GHGs (Figure 2). The pre–farm emission in UTHR was around equal to the emissions of CTHR, 8.3% lower than UTLR and 5.5% lower than CTLR due to higher productivity and increased input efficiency.

Overall, the pre–farm emissions were significantly lower than on–farm emissions for CTLR, CTHR, UTLR and UTHR (9.4%, 7.5%, 11.4%, and 9.9% in the 100 years horizon of on–farm emissions). The production of pesticide and fertilizer alone contributed 8%, 6%, 6% and 6% to the total of CO_2–eq GHG emissions for the 100 years horizon during the pre–farm stage for UTLR, UTHR, CTLR and CTHR, respectively.

3.2 GHG emissions from pre–farm and on–farm stages

Pre–farm stage: The pre–farm stage in the current study produced significantly lower emissions compared to studies conducted in other climates. Differences were also observed among pre-farm emissions of different treatments ($p>0.05$). The lower pre-farm emissions in this study are due to the lower overall level of inputs (fertilisers, fungicides, insecticides, etc.) used in comparison with yields obtained, to the use of natural gas as a feed–stock for urea production and electricity generation and to light vehicles that are used for transporting inputs to paddy fields in the region of study.

The results of current research in the case of pre-farm emissions are lower than other similar studies of Thanawong et al. (2014; lower by 0.3 tonne CO_2–eq to 0.6 tonne CO_2–eq tonne^{-1} rice), Xu et al. (2013: 0.53 tonne CO_2–eq lower in Jiangsu to 0.73 tonne CO_2–eq tonne^{-1} rice lower in Guangdong), Wang et al., (2010; around 20% less to the total GWP per tonne of rice) and Blengini and Busto, (2009; around 0.16 tonne CO_2–eq tonne^{-1} rice lower in 100-year time horizon) as these used carbon intensive inputs and had low yields (i.e. low yields higher per tonne base emissions). Wang et al. (2010) found that rice crops with yields of 8.8 Mt ha^{-1} accounted for higher emissions than rice yielding 9.3 Mt ha^{-1} due to more than double the inputs in the former case (Brodt et al. 2014). Fusi et al. (2014) also found 30–40% of the total GHGs came from pre–farm inputs manufacturing (mainly fertiliser production), transport and rate of input use per tonne of harvest. The present study also contradicted the results of Blengini and Busto (2009) who found around 35% of gross energy (GER) and almost 40% of NRER (Non-Renewable Energy Requirement) required for white milled rice production were contributed by pre–farm inputs which consequently contributed to high emissions. By contrast with the wetland rice cropping systems, Barton et al. (2014) studied upland cropping systems in a semi–arid environment and found that the contribution of pre–farm processes could vary between 28 (0.1 tonne CO_2–eq tonne^{-1} grain in lupin–wheat rotation without lime per year) and 55% (0.35 tonne CO_2–eq tonne^{-1} grain in wheat–wheat rotation with lime application per year) of total GHG emissions depending on the application of lime. In the same semi–arid climate, Biswas et al. (2008) found that pre–farm stages accounted for 58% (0.1 tonne CO_2–eq tonne^{-1}) of the total emission for wheat production. While soil emissions of CH_4 and N_2O were relatively low under upland rice or dryland wheat cropping, with flooded rice production, the high CH_4 emission results in a higher percentage of on–farm emissions. Finally, the emissions during the pre–farm stage are mostly CO_2 emissions by contrast with CH_4 and N_2O that have much greater GWP, and are predominantly emitted during the on–farm stage.

On–farm stage: The contribution of on–farm processes varied between 89 and 93% (in the 100 years horizon) of total GHG emissions during wetland rice production. The on–farm GHG emissions from CTLR and CTHR were 91 and 93% of the total emissions while the percentages were 89 and 90% (100-year horizon) in the case of UTLR and UTHR, respectively. The CTHR contributed the highest on–farm emissions resulting from lower productivity and higher methane emissions. Among the main factors affecting emissions from agriculture are cultivation practices adopted (Lal, 2004), input use (Cheng et al., 2011) and soil fertility status (Duby and Lal, 2009; Gupta et al., 2009). The fuel consumption for irrigation and land preparation and harvesting (0.6–0.9%) alone accounted for 14 to 19% of the total emissions of the on–farm emissions. This is supported by the study conducted by Islam et al. (2013) and Khan et al. (2009) who found that irrigation is the major share of energy inputs for rice production. In addition, Thanawong et al. (2014) also found that irrigated rice produced higher on–farm emissions than rain-fed rice growing as the emissions of CH_4 of the former were almost double those of rain-fed rice. Other studies also confirmed that water and N management, organic matter (OM) application and crop establishment practices regulate GHG emission (Yagi et al., 1996; Nishimura et al., 2004). All these factors (e.g. water, high N application, tillage practices and crop residues) are integral to wetland rice production but they are favourable for GHG emissions. In addition, these practices also influenced CH_4 and N_2O emissions through the changes of soil properties (e.g., soil porosity, soil temperature and soil moisture, etc.) (Al–Kaisi and Yin, 2005; Yao et al., 1999; Yao et al., 2009). Bockari–Gevao et al. (2005) reported that the operational energy consumed by tillage on average was 1.75 GJ ha^{-1} (48.6% of the total operation energy) which was the highest contributor among the operational requirements but UT increases energy productivity by up to 12% (Islam et al., 2013). The use of UT also saved ~ 67 % fuel consumption due to fewer passes per unit area by machinery and thereby less distance travelled for seedling establishment (Islam et al., 2012) leading to less emissions under UT. In the following section, we identify the hotspots for GHG emissions.

3.3. Identifying hotspots contributing to significant GHG emissions

The CH_4 emissions from paddy fields accounted for the major portion (60–67% in the 100-year time horizon) of GHG emissions in all treatments/practices, followed by farm machinery use (13–16%), CO_2 emissions from soil (9–10%), production of inputs (6–9%) and transport of inputs (2–3%) (Figure 2). Contributions to GHG emissions from CH_4 in the 100-years horizon ranged from 60% for UTLR practice to 67% for CTHR practice.

The IPCC (2007) substantiated that the cultivation of irrigated rice is responsible for up to 12% of anthropogenic methane (almost half of total agricultural CH_4 emission) efflux. The results of the current study differ from many other grain crop LCA studies in terms of hotspots. Nemecek et al. (2008) conducted LCA on upland crop (oilseed rape –wheat –spring peas –winter wheat –winter barley) rotations and found N_2O was the key contributor of GHG emissions (CO_2–eq). Indeed, N_2O has been found to be the dominant GHG in most LCA studies of arable agriculture (Woods et al., 2008; Eshun et al., 2013; Brock et al., 2012) because aerobic conditions with intermittent waterlogging stimulate the emission of N_2O (Flessa and Beese, 1995), whereas CH_4 emission in aerobic soils can even be negative due to microbial CH_4 oxidation (Barton et al., 2013, 2014).

Interestingly, the hotspots in the current research were the same as those in pasture production (beef, milk etc. by ruminants) which also resulted in the highest enteric CH_4 emission (63% for beef production in Beauchemin et al., 2010; 49% for milk production in Casey and Holden, 2005; 50% in beef production in Vergé et al., 2008; 83–90% in sheep meat and wool production in Biswas et al., 2010). However, the processes generating CH_4 emissions are different in these two cases: belching of CH_4 emissions from ruminants for the pasture industries and anaerobic decomposition of organic residues in wetland rice production.

The hotspot results of the current study were similar to the LCA conducted by Harada et al. (2007) and Pathak et al. (2005) who also found that CH_4 was the highest contributor of GHG emission (around 60%) for rice production. Again, Fumoto et al. (2008), Hokazono and Hayashi (2012) and Hatcho et al. (2012) who evaluated wetland rice cultivation in Japan, and Drocourt et al. (2012) who evaluated rice cultivation in France, identified CH_4 emissions as the key contributor to GWP. Fusi et al. (2014) also found CH_4 emissions from the soil, due to the anaerobic decomposition of organic matter, was by far the main emission source for wetland rice cultivation (40%). Whilst these studies found CH_4 as the dominant source of GHG emissions, their contributions were still lower than the values in the current analysis (i.e. 76%, 0.67 tonne CO_2–eq tonne^{-1} of rice production for UTLR, 0.76 tonne CO_2–eq tonne^{-1} of rice production for UTHR). Also Drocourt et al. (2012) explained that the retention of high residue levels in addition to anaerobic decomposition caused high CH_4 emission from rice fields. The present study, therefore, confirms that CH_4 emissions resulting from anaerobic decomposition of organic matter in unpuddled flooded fields is the dominant emission source regardless of residue levels.

The farm machinery use accounted for the second largest contribution (13–16% of total) followed by the emissions of carbon dioxide (9–10% of total) from soil during the on–farm stage. Blengini and Busto (2009) in their LCA of rice production in Italy also identified on–farm methane emissions, farm machinery use and emissions due to fertilizer applications as the main hotspots, in that order of priority. The soil N_2O emissions comprised only 2–3% of total emissions for different treatments in the present study (Figure 2).

3.4 Overall GHG emissions

Total pre–farm and on–farm emissions from production of 1 tonne of rice in the Eastern Gangetic Plain were 1.11, 1.19, 1.33 and 1.57 tonne CO_2–eq for UTLR, UTHR, CTLR and CTHR, respectively, in the 100-year time horizon. Our results for conventional puddling are similar to studies conducted by Hokazono et al. (2009) as the GHG emissions in Japan from pre–farm and on–farm stages were 1.51, 1.34 and 1.62 tonne CO_2–eq tonne^{-1} of rice production for the conventional, sustainable and organic farming systems, respectively. Farag et al. (2013) revealed that GHG emission for rice within the same system boundary (i.e. up to farm gate) was 1.9 t CO_2–eq tonne^{-1}. In addition, Ryu et al. (2013) estimated the carbon footprint under puddled production of rice was 2.21 t CO_2–eq tonne^{-1} up to the harvest (farm–gate) periphery. Therefore, the GHG emission values of 1.33–1.57 tonne CO_2–eq tonne^{-1} of puddled transplanted rice in the current study were closely similar to values reported for rice produced in other locations under different climatic conditions.

3.5. Predominant GHG emissions from field

Given that CH_4 was the dominant GHG emission further analysis is needed on the reasons for these emission values and potential for further decreases (Figure 3). Long–term increase in residue incorporation in the field under study might increase CH_4 emission (Kanno et al., 1997) and the prolonged reducing conditions with two rice crops in the previous 9 months may have increased generation of CH_4 (Ponnamperuma, 1972; Takai and Kamura, 1966; Yu and Chen, 2004). The on–farm CH_4 emission can be reduced by ensuring minimum soil disturbance, and by judicious water and crop residue management. For example, mid–season drainage of soils for a short period with residue retained might favour CO_2 emissions rather than CH_4 (Yagi and Miami, 1990). The decreased soil disturbance may maintain higher redox potential under UT that limits emissions of CH_4. The redox potential values varied among tillage and residue retention practices with range of Eh values from –200 to –250mV for CTLR and CTHR and –150 to –200 mV for UTLR and UTHR (data not shown). If so, modification of the strip tillage may be designed to achieve even less soil disturbance. However, research would be needed to ascertain how to avoid stimulating N_2O emission from the present 2–3.5% of the total direct on–farm GHG emitted for rice production in the Eastern Gangetic Plains. Comparatively small increases in emissions of N_2O can contribute substantially to GHG emissions. Xing (1998) found that rice fields were a key source of N_2O emission, accounting for 22% of the total emission from cropland in China (Xing 1998). On the other hand, work on the LCA of rice by Nishimura et al. (2004), Wassmann and Dobermann (2006) and Six et al. (2004) were similar to our results as they found that the rice fields contribute 2–8% of the total amount of direct on–farm emissions. The rate of N_2O emission from wetland rice field was small in the study of Minami and Fukushi (1984). The present study found 0.2 (UTLR) to 0.4% (CTHR) of the applied N fertilizer was emitted as N_2O. This value is lower than the default value (1%) of N_2O loss from mineral N applied as fertilizer used by the IPCC (2006). Most of the produced N_2O might be reduced to di-nitrogen (N_2) in wetland rice (anaerobic) condition (Nishimura et al., 2004).

Soil carbon sequestration may become important in the UT cropping systems over time due to decreased soil disturbance (strip tillage) especially with increased residue retention. It may take several more years before the changes in soil organic carbon reach equilibrium with the reduced soil disturbance in UT and the increased residue retention. Studies on soil organic carbon are underway at the present site where tillage and residue treatments have been practiced for more than 4 years.

The other crops in the cropping system now under study are mustard (*Brassica campestris* L.) which is usually grown in cool–dry season (from mid-October to middle March) and transplanted *aman* rice which is grown in the monsoon season (from early July to middle October and characterised with high rainfall and humidity). Life cycle analysis studies are also required on these crops in order to complete a temporal and spatial assessment of the life cycle greenhouse gas mitigation potential in the intensive rice-based cropping systems of the Eastern Gangetic plain.

4. Conclusions

The present study estimated GHG emission mitigation potential associated with the application of the recently developed UT of rice and with increased residue retention in the Eastern Gangetic Plains. The conventional puddled transplanting with high residue retention (CTHR) emitted (1.6 tonne CO_2–eq) about 1.4 (on the basis of 100-year time horizon) times more GHG emissions for one tonne of rice production than the best mitigation option which was strip tillage followed by unpuddled transplanting with LR (UTLR). Applying UTLR in the wetland rice system of the Eastern Gangetic plain can reduce GHG emissions to 1.1 tonne CO_2–eq tonne^{-1} rice production in the 100-year time horizon.

The on–farm stage contributed the highest portion (e.g. 89– 93% in 100 years) of the total GHG emissions due mostly to high GHGs emission and to farm machinery use. Regardless of tillage or residue retention, CH_4 was the predominant GHG emitted from the production of 1 tonne of rice in the Eastern Gangetic Plains due to anaerobic soil conditions for rice production. We recommend carrying out additional streamlined LCA studies for all the crops of the rice–based cropping system to assess the GWP of the conservation agriculture production practices in diversified rice growing areas.

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1 Table 1. Life cycle inventory of pre–farm and on–farm inputs and outputs for one tonne of
2 rice production in the Eastern Gangetic Plain

Inputs (units)	Establishment treatments			
	CTLR[a]	CTHR[b]	UTLR[c]	UTHR[d]
Pre–farm				
a) Seeds and chemicals (kg tonne^{-1} of rice production)				
1. Seeds	7.15	6.8	7.28	6.74
2. Nitrogen	19.4	18.4	19.9	18.3
3. Phosphorus	8.35	7.92	8.5	7.86
4. Potassium	12.8	12.1	13.0	12.1
5. Sulfur	1.70	1.61	1.73	1.60
6. Zinc	0.48	0.46	0.49	0.45
7. Boron	0.50	0.38	0.41	0.38
8. Fungicides	0.25	0.24	0.26	0.24
9. Herbicides	0.29	0.27	0.29	0.27
10. Insecticides	0.45	0.42	0.45	0.42
b) Transport (km for road + t–nm for sea)[1]				
1. Urea	62.8	59.6	63.9	59.2
2. Triple superphosphate	83.1+544	78.9+516	84.6+554	78.3+512
3. Muriate of potash	83.1+380	78.9+360	84.6+387	78.3+358
4. Gypsum	83.1+380	78.9+360	84.6+387	78.3+358
5. Zinc	83.1+380	78.9+360	84.6+387	78.3+358
6. Boric acid	83.1+265	78.9+252	84.6+270	78.3+250
7. Insecticides	66.3	62.9	67.5	62.4
8. Fungicides	81.9	77.7	83.3	77.1
9. Herbicides	83.1+173	78.9+164	84.6+176	78.3+163
c) Farm machinery (US$ tonne^{-1} of rice production)				
1. Power Tiller/Versatile Multi–crop Planter	0.10	0.10	0.05	0.05
2. Harvester	0.06	0.05	0.06	0.05
3. Irrigation pump	1.85	1.76	1.89	1.75
d) Farm machinery transport (km for road + t–nm for sea)				

1. Harvester	83.1+265	78.9+252	84.6+270	78.3+250
2. Power tiller	83.1+265	78.9+252	–	–
3. VMP	–	–	84.6+270	78.3+250
4. Irrigation pump	83.1+265	78.9+252	84.6+270	78.3+250
On–farm (litre tonne^{-1} of rice production)				
1. Power tiller/Versatile Multi–crop Planter	2.39	2.33	0.99	0.98
2. Irrigation pump	1.53	1.45	1.55	1.44
3. Harvester	65.5	66.7	62.2	61.7
Rice yield (tonne/ha)	6.29	6.63	6.18	6.68

[1]t–nm=tonne–nautical mile; [a]puddled transplanting with low residue retention (CTLR); [b]puddled transplanting with high residue retention (CTHR); [c]unpuddled transplanting with low residue retention (UTLR) and [d]unpuddled transplanting with high residue retention (UTHR)

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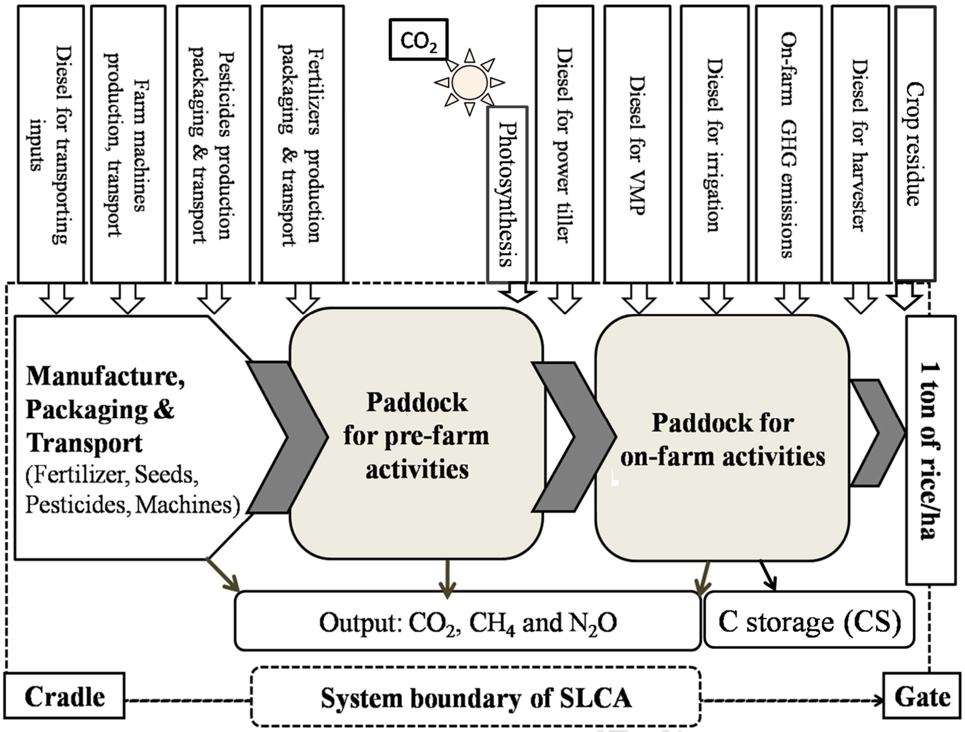

Fig. 1. System boundaries and input–output relationship adopted in the work

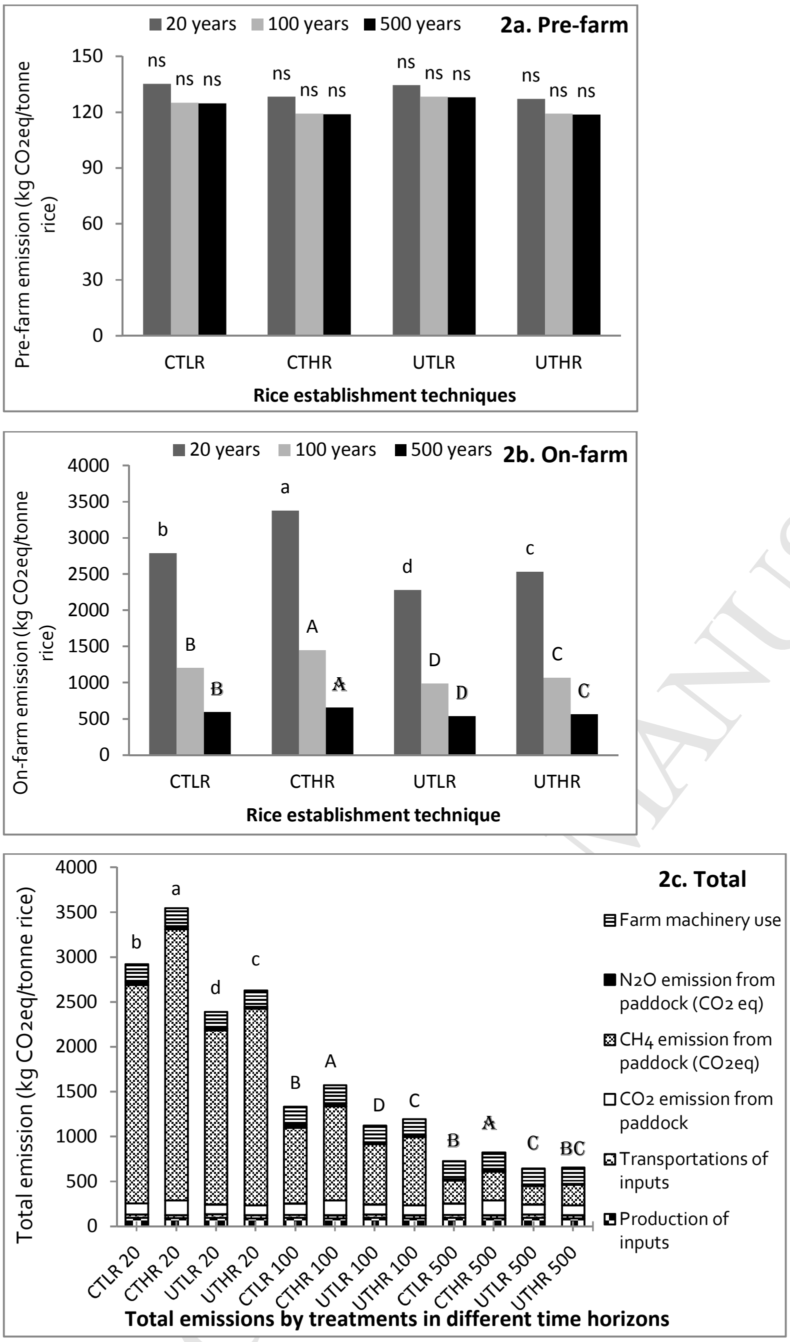

Fig. 2 (2a-pre-farm and 2b-on-farm emissions; 2c-total emissions showing contributions from different sources). Life cycle greenhouse gas emissions produced per season for one tonne of rice production as influenced by crop establishment techniques and residue retention ($p<0.05$). Standard error (SE; ±) values for on-farm emissions are 58.2, 32.0 and 16.3 and for total emissions are 57.7, 62.8 and 13.1 over 20-, 100- and 500-year time horizons, respectively. Bars containing the same letter above them are not significantly different at

$p<0.05$. Comparisons are made among emissions converted to CO_2–eq according to GWPs of CO_2, CH_4 and N_2O over 20-, 100- and 500-year time horizons. [Legend: CT–Conventional puddled transplanting of rice; UT–Unpuddled transplanting of rice; LR–Low residue retention level; HR–Increased residue retention level]

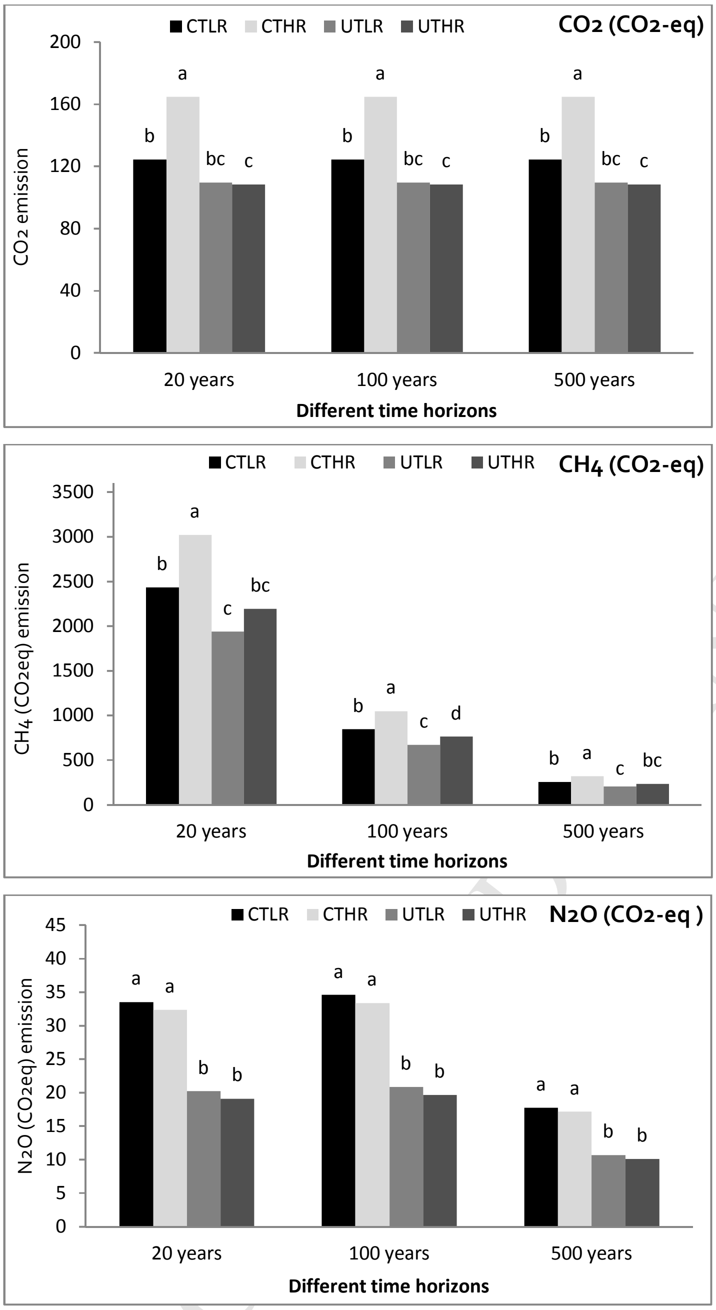

Fig. 3. Effect of rice establishment techniques and residue retention on on–farm emission of greenhouse gases (CO_2 equivalent; $p<0.05$). Bars with the same letter above them are not significantly different at $p<0.05$. Comparisons are made among emissions converted to CO_2–eq according to GWPs of CO_2, CH_4 and N_2O over 20-, 100- and 500-year time horizons. SE (±) for CO_2 emission is 4.7. SE (±) values for CH_4 emissions are 124.6, 43.5 and 13.5 and for N_2O emissions are 0.3, 0.2 and 0.2 over 20-, 100- and 500-year time horizons, respectively.

[Legend: CT–Conventional puddled transplanting of rice; UT–Unpuddled transplanting of rice; LR–Low residue retention level; HR–Increased residue retention level].

Highlights

- Wetland rice is a major emitter of greenhouse gases and needs new mitigation strategies
- A streamlined LCA was studied for puddled and unpuddled rice planting with current and increased residue retention
- Non-puddling with low residue retention was the most effective GHG mitigation option
- Puddling soil regardless of residue retention was the least effective GHG mitigation option
- Soil CH_4 and on–farm machinery use were the major GHG emission sources.