Model. Earth Syst. Environ. (2017) 3:1691–1705
DOI 10.1007/s40808-017-0368-y

ORIGINAL ARTICLE

Evaluation of the environmental impacts of rice paddy production using life cycle assessment: case study in Bangladesh

Abdun Naqib Jimmy[1] · **Nazmul Ahsan Khan**[1] · **Muhammed Noor Hossain**[2] · **Mohammad Sujauddin**[1]

Received: 10 July 2017 / Accepted: 11 August 2017

Abstract The world is heading towards sustainability. Environmental dimension of sustainability is getting momentum and therefore it is imperative to know the peril through environmental load of a product, process, or activity throughout its life cycle. This study focuses on life cycle assessment (LCA) of rice production in Bangladesh, the fourth highest producer of rice in the world. The objective of this study was to estimate the different environmental impacts from production of paddy rice, in a typical scenario, and identify the environmental hotspots. A life cycle impact assessment has been carried out using ReCiPe methodology, which consists of 18 midpoint impact indicators. The resulting LCA has pointed out the magnitude of impact per kg of paddy produced from the harvested field; a CO_{2eq} emission of 3.15 kg as global warming potential, a P_{eq} emission of 0.00122 kg as freshwater eutrophication, fossil depletion of 0.68 kg oil_{eq}, a 1,4-DCB-kg oil_{eq} emission of 1.15 kg as human toxicity, a NMVOC emission of 0.016 kg as particulate matter formation, a N_{eq} emission of 0.0154 kg as marine eutrophication and use of 2.97 m^3 of water for irrigation purpose. Contribution analysis shows that irrigation and emissions from paddy field are the most environmentally burdening stages across all major impact categories. Manufacture of fertilizer and pesticide also play a significant role in putting environmental load. The application of this study helped to identify improvement opportunities to reduce environmental impacts within this and related production systems, and demonstrated its usefulness in setting priorities to realize these opportunities.

Keywords Life cycle assessment · Rice paddy · Impact evaluation · Cultivation · Bangladesh

Introduction

To meet the challenges posed by climate change and other environmental adversities, many tools and indicators have been developed to assess the environmental impacts of various systems (Finnveden et al. 2009; Nie et al. 2011). Life cycle assessment (LCA) is one of these major tools that can evaluate environmental burden posed by a product or an activity (Ayres and Ayres 2002; Haes 2002; Rebitzer et al. 2004; Finnveden et al. 2009).

LCA is a widely accepted impact assessment tool in the field of industrial ecology (Haes 2002). It can methodologically determine the environmental impacts attributable to each life phases of a product's entire life cycle (Consoli et al. 1993; Miettinen and Hämäläinen 1997; Rebitzer et al. 2004). Therefore, LCA is instrumental in obtaining a comprehensive picture of a product's environmental performance during its life span, to enable informed decision and policy making (Miettinen and Hämäläinen 1997). Finnveden and his colleagues (2009) also reported that due to LCA's unique methodology, it avoids burden-transfer from one phase of life cycle to another, or from one environmental impact to another. This comprehensive scope of LCA makes it a very robust tool for environmental impact assessment and assist in discovering sustainable options. Life cycle assessment has also seemingly become the gold standard for emerging environmental certification

---

✉ Mohammad Sujauddin
mohammad.sujauddin@northsouth.edu

[1] Department of Environmental Science and Management, North South University, Bashundhara, Dhaka 1229, Bangladesh

[2] Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden

and labeling programs (Pelletier 2014). This is a testament that LCA has the capacity to bridge consumers and producers of the world, integrating environmental considerations. Therefore LCA plays an important role for authorities, individuals and all industries in achieving a wide range of benefits (Miettinen and Hämäläinen 1997; Roy et al. 2009).

The world population stands at 7.4 billion in 2016 (Population Reference Bureau 2016). To sustain them all, we have taken over almost half of the world's land mass and turned it into our primary source of sustenance and livelihood (Owen 2005). Agricultural food production is putting a huge amount of environmental burden (Tilman et al. 2001; Garnett 2011). The result of agriculture and the intensity of cultivation practice leave a lasting and irreversible impact on the environment (Önder et al. 2011). Agricultural practices consequently contributes heavily to greenhouse gas emissions, soil fertility, biodiversity loss and release of toxic substances in the ecosystem among other pollutants (McMichael et al. 2007). 10–12% of the global heating reportedly comes from agricultural activities (Mogensen et al. 2015; Mosleh et al. 2015). Besides climate change, agricultural practices contribute to an array of environmental impact categories (Önder et al. 2011).

Hence there is an urgency to evaluate both our production and consumption pattern; before the environmental impacts associated with food production exceeds natural boundaries. Soussana (2014) reports that using life cycle perspective may lead to breakthroughs in the sustainability assessment of food systems; it is therefore unsurprising that literature of LCA to food systems has been thriving recently (e.g. Notarnicola et al. 2012, 2017; Nemecek et al. 2016; Goossens et al. 2017). There is an abundance of literature related to LCA on agricultural crops such as potato (Mattsson and Wallén 2003; Veisi et al. 2017), tomato (Andersson et al. 1998; Nienhuis and de Vreede 1996; Van Woerden 2001; Anton et al. 2005; Roy et al. 2008; Torrellas et al. 2012), sugar beet (Bennett et al. 2004), wheat (Brentrup et al. 2004; Charles et al. 2006), dry pea and lentil crops (MacWilliam et al. 2014) and apple (i Canals et al. 2006; Goossens et al. 2017). However, despite being the fundamental source of sustenance and environmentally intensive, we are still unaware of full phase LCA case study of rice, especially in developing countries. Our study is an attempt to fill this gap.

Among all agricultural commodities, rice is the most important (Breiling et al. 1999; Khush 2005; Roy et al. 2009). Rice is the cardinal diet of over half the world's population (FAO 2011; Muthayya et al. 2014). Currently grown in more than 100 countries and all continents except Antarctica, rice is integral for world's economy and food security. With 90% of world's production (Muthayya et al. 2012), Asia is the world's largest rice-producing and rice-consuming region and is also becoming an increasing food staple throughout Africa (de Miranda et al. 2015).

We are aware about some notable LCA studies on rice in developed countries viz. Italy (Blengini and Busto 2009), Japan (Breiling et al. 1999; Harada et al. 2007; Hokazono et al. 2009; Hatcho et al. 2012; Yoshikawa et al. 2012; Hokazono and Hayashi 2015), USA (Brodt et al. 2014). However, LCA as a tool is largely unexplored in developing countries. World rice consumption estimate for 2013–2015 was reported as 490,804,000 tonnes per year, where developing countries alone consume 471,919,000 tonnes (96%) (OECD/FAO 2016). The volume of consumption in this region alone provides compelling ground that LCA should be promoted in developing countries to become standard practice in agriculture sector for sustainable and continuous generation of crops.

Bangladesh is the epitome of rice based nation, as it stands fourth in top rice producing countries of the world, as well as holds the second place for rice consumption per year per capita (169.5 kg per capita), only second to Vietnam (OECD/FAO 2016). Agriculture makes up 15.1% of Bangladesh's GDP (CIA 2017). The importance of agriculture in the country also lies in the fact that almost half of the population earns their livelihood in this sector, as per the world bank database (The World Bank 2010). Despite being a small country, Bangladesh produces a wide range of crops viz. rice, wheat, maize, pulses, tobacco, cereal, potato, jute, oil seeds, spices, chilies, onion, tea, drugs and narcotics, vegetables, tomato, fruits and sugar crops (BBS 2012) (Fig. 1). Although Bangladesh is the fourth highest producer of rice, it is the smallest country to have such a high yield of production. An incredible 80% of the total country area is cultivated for rice harvest (CIA 2017; USDA 2017).

However, the agriculture scene of the country is tethered with crude agricultural practice, use of conventional, outdated machines (BBS 2012) and obsolete pesticides (Parveen and Nakagoshi 2001). Bangladesh also tend to have intense cropping practices. With triple cropping system in a season, the agricultural inputs can environmentally be burdening. Especially to meet food demand, agriculture has been intensified through use of chemicals, and high yielding variety of crops; a stark contrast of cultivation practice as done by developed parts of the world (Uddin and Takeya 2006). Organic farming is also not prominent in the culture of Bangladesh (Hoque 2012). Although the nation is well suited for agriculture in terms of climate and soil type, high production of rice typically equates to tremendous consumption of water through irrigation (Chowdhury 2010). Especially in terms of application of commercial fertilizers, Bangladesh is within top 20 most fertilizer using country in the world (FAO 2017). This is a staggering number, considering the small size of the country and high fertile soil. According to FAO

Fig. 1 Annual production of prominent agri-crops in Bangladesh from 2004 to 2014 (Source: FAO 2017)

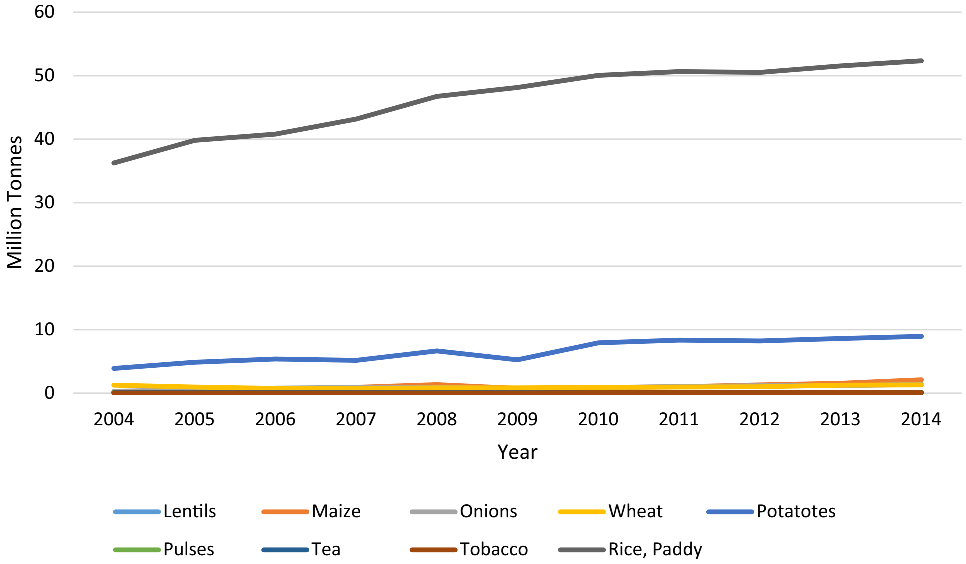
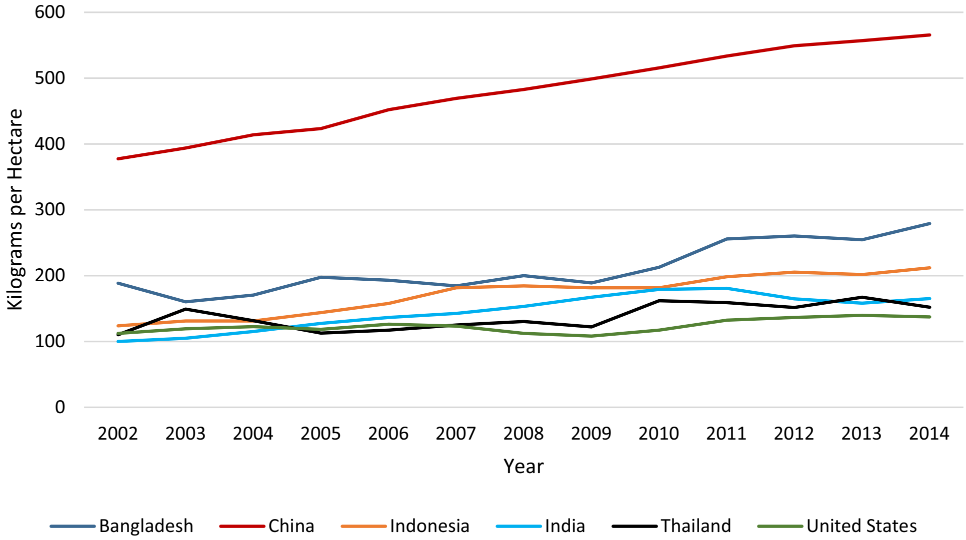


Fig. 2 Fertilizer use among highest rice producers (Source: FAO 2017)



statistics (FAO 2017), Bangladesh is only behind China in terms of volume of fertilizers used in agriculture per hectare area (Fig. 2).

Rice paddy production in Bangladesh have increased gradually over the years, and is not likely to slow down due to constantly increasing food demand. Bangladesh also export surplus rice variety overseas, which contribute to the country's welfare (BRRI and BBS 2016). Given that rice is a highly produced crop in South Asia, there is dire need to evaluate its environmental performance at each step of its life. The demand for food production is projected to increase within 2050, by a large margin. If this trend continues, the environmental stress will increase due to increase in rice production to meet future demand. Hence, conducting LCA on rice is not of national interest, but urgent for global context as well.

According to FAO (2017), over 30% of carbon dioxide equivalent emission in Bangladesh are contributed from rice cultivation. Through life cycle assessment, it will be possible to identify environmental hotspots/weakspots in its life cycle at every phase of production, which can then be used to prioritize stages of the production chain needing improvement to mitigate harmful emissions. By conveying the results of an LCA, it may be possible to introduce new policies and put a break to the vicious cycle of intense cropping practices. While it is important that rice production increases with demand, the production process must be streamlined as such, that it performs optimally not only financially but from an environmental standpoint. It is urgent that we look for opportunities to find room for improvement, to meet demands and improve yield without compromising environmental integrity or public health.

Use of LCA in industries of Bangladesh is also unheard of. However, the institutional set-up of the society can be rapidly changed through popularizing the use of LCA in the industries of Bangladesh. Once the appeal of benefits LCA can bring in optimizing resources is understood, there will be an increased enthusiasm in keeping comprehensive and up-to-date directories for transparency between producers and consumers. In light of that, the LCA on rice paddy production is the first attempt at a gate to gate study in this region. As a consequence of the significant contribution of the results in the case study, use of LCA will be popularized, so that, in the long run, it becomes statutory to use the comprehensive and holistic tool to optimize processes in an activity or production operation in Bangladesh or any other developing countries of the world. Toxic substances and environment stressing activities are probably a larger problem in developing countries like Bangladesh, and should get more attention from LCA practitioners (Haes 2004).

LCA on rice in Bangladesh has been done on one occasion alone, as author Roy et al. (2007) conducted a life cycle assessment of CO_2 emission from parboiled rice production and compared it with untreated system of rice production. However, the mentioned author's case study did not include LCA during the agriculture (cultivation) phase of rice production; which is the production of paddy rice in the field. Hence this study adds a new nexus by establishing the total impact that is enclosed in the generation of paddy rice in a typical scenario, to provide an average scenario of impacts on the environment. This will provide environmentally conscious policy makers, producers and consumers with comprehensible information to make informed steps, with the help of LCA—to explore different options and greener alternatives.

Methodology

Overview of the methods

The life cycle assessment methodology has been used to evaluate the environmental profile of general rice paddy farming. Standard guidelines for life cycle assessment and more specifically, life cycle assessment of agricultural crops were followed (Tillman and Baumann 2004; Nemecek et al. 2014). Goal and scope definition is aimed at establishing the study objectives, functional unit (FU), and system boundaries and data sources.

Life cycle inventory (LCI) stage details out all the environmental inputs and outputs at each stage of the case study within the defined system boundary. Life cycle inventory is the backbone of an LCA (Jiménez-González et al. 2000). The objective of the inventory is to create a model of the product or activity identified during defining the system boundary in the goal and scope definition stage. Primary data collection for this stage was mined from conducting field survey from two different farms in Bangladesh, in Meherpur and Baliakandi, where about 20 farmers were interviewed. As information from farmers can result in varying information, as cultivation practice can differ from region to region, also depends on farmer's individual financial capacity and resource availability, private communication with rice research scientific officer at Bangladesh Rice Research Institute (BRRI) was also established, for reliable data, that would serve the purpose of modelling the LCA according to typical cultivation practice. Data were also taken from literature study and cited accordingly.

Life cycle impact assessment quantifies the relative importance of all the environmental burdens identified in the LCI by analyzing their influence on selected environmental categories. Life cycle impact assessment is composed of classification and characterization that converts LCI result into an indicator representative of each impact category. For this analysis, the ReCiPe[1] Midpoint (H) methodology was employed (Huijbregts et al. 2017). ReCiPe uses 18 midpoint indicators and three endpoint indicators. Endpoint was not considered in this study. The midpoint indicators are in the table below (Table 1).

LCA of rice paddy in Bangladesh (baseline scenario)

Rice paddy production in Bangladesh has technically similar practice as other countries in the world, but differing in intensity, use of technology and cultivar variety. It was still important to establish the steps of paddy cultivation, by interviewing farmers in the field, personally communicating with Bangladesh Rice Research Institute and comparing literature studies. Details of data gathered and sources are discussed in subsequent sections.

The LCA model describes a typical farm in Bangladesh. Average quantity of inputs applied (fertilizers, pesticides, etc.) are taken into consideration. Average yield harvested since 1995 to 2015 roughly corresponds to 4 t/ha (FAO 2017). The cultivar is not specified as the case study is based on average grain yields over a long period; this exclusion is similar to authors who have studied the life cycle assessment of milled rice in Italy (Blengini and Busto 2009).

---

[1] "The method has been given the name ReCiPe as it provides a 'recipe' to calculate life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to this project and the major collaborators in its design: RIVM and Radboud University, CML, and PRé Consultants" in https://www.pre-sustainability.com/faq/what-does-the-acronym-recipe-mean.

Table 1 List of ReCiPe midpoint indicators

Name of indicator	Description	Abbreviation	Reference unit
Freshwater ecotoxicity	Phosphorus concentration	FETPinf	kg 1,4-DCB$_{eq}$
Natural land transformation	Transformation	NLTP	M^2
Climate change	Infra-red radiative forcing	GWP$_{100}$	kg CO$_{2eq}$
Metal depletion	Metal resource depleted	MDP	kg Fe$_{eq}$
Terrestrial acidification	Base saturation	TAP$_{100}$	kg SO$_{2eq}$
Agricultural land occupation	Land occupation	ALOP	M^2
Marine ecotoxicity	Hazard-weighted concentration	METPinf	kg 1,4-DCB$_{eq}$
Particulate matter formation	PM10 intake	PMFP	kg PM10$_{eq}$
Terrestrial ecotoxicity	Hazard-weighted concentration	TETPinf	kg 1,4-DCB$_{eq}$
Water depletion	Amount of water withdrawn	WDP	M^3
Urban land occupation	Land occupation	ULOP	M^{2}a
Fossil depletion	Fossil resource depleted	FDP	kg oil$_{eq}$
Human toxicity	Hazard-weighted dose	HTPinf	kg 1,4-DCB$_{eq}$
Freshwater eutrophication	Phosphorus concentration	FEP	kg P$_{eq}$
Photochemical oxidant formation	Photochemical ozone concentration	POFP	kg NMVOC
Ionising radiation	Absorbed dose	IRP_HE	kg U235$_{eq}$
Ozone depletion	Stratospheric ozone concentration	ODPinf	kg CFC-11$_{eq}$
Marine eutrophication	Nitrogen concentration	MEP	kg N$_{eq}$

Source: Goedkoop et al. (2009) and Huijbregts et al. (2017)

System boundaries and functional unit (goal and scope)

For the present analysis, the LCA model was carried out as “gate to gate” in the cultivation field (Fig. 3) and not a complete “cradle to grave”, the activity starts with soil cultivation after the harvest of the previous crop. The activity ends with the harvest of rice grains and subsequent burning of crop residues.

The system boundary have been divided into foreground system and background system. Foreground system is all the agricultural activity and inputs that are made after land is prepared to grow the rice paddy after harvesting of previous crop is finished. The agricultural input that are taken into consideration include all machine operations, corresponding infrastructure, and fuel use. Machine operations are: rotary tillage, the application of pesticides and fertilizers using machines, irrigation pumps and harvesters. Amount of pesticides, fertilizers and rice seed are accounted for. These are the foreground system, or the immediate agricultural activities within system boundary of the gate to gate study. The foreground activity produces environmental load as shown in the figure (Fig. 3), and rice paddy as the final outcome. The life cycle inventory created for the production of rice paddy is for foreground activity and are based on primary and secondary data.

The LCA model also includes background system, which is all the upstream activities that are required to complete the foreground activity. Namely, the production and manufacturing of plant management applications, machines, diesel and their respective transportation to the farm. The upstream activity also puts environmental burden, and the impact is accounted for during the life cycle impact assessment phase of this study. The data for background system has been obtained from ecoinvent database version 3.3, as discussed in later chapters.

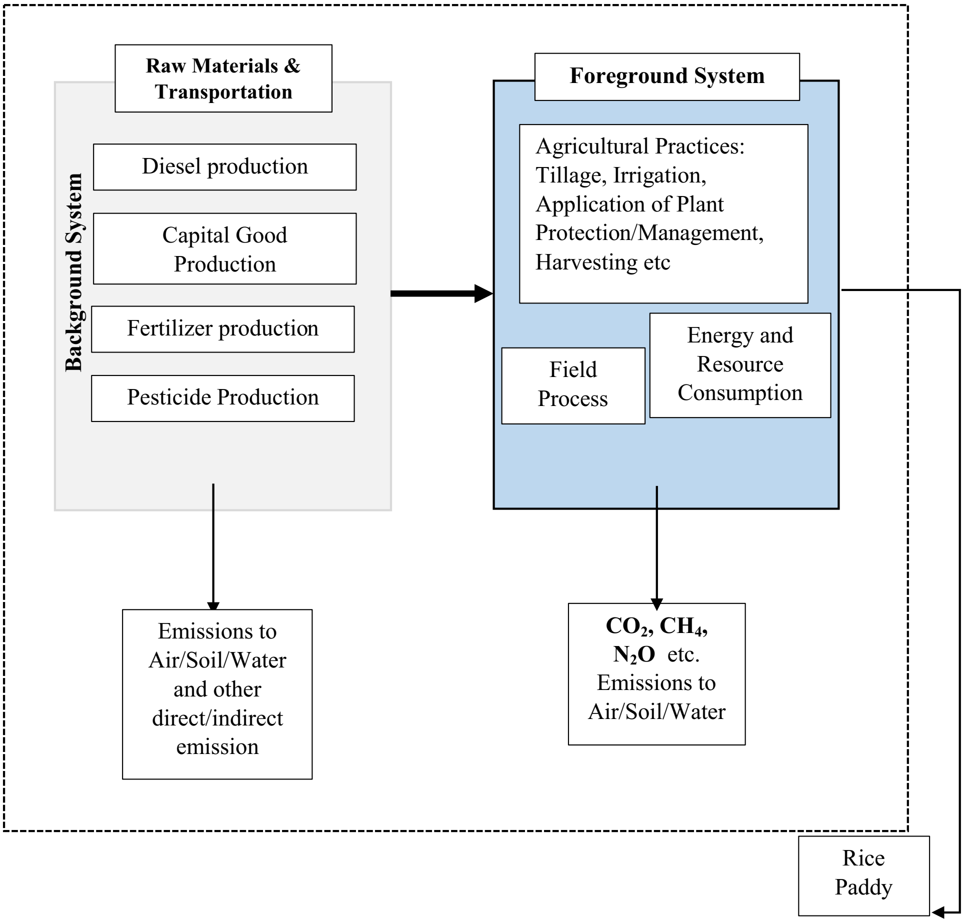
Rice seedlings are transplanted manually by throwing the seedlings in the standing water. Paddy rice is grown under submerged conditions (50 cm standing water for approximately 150 days, assuming non-flooded conditions 1 week prior to harvest). Further, direct field emissions and land use change are included. The inputs of seeds, irrigation water, fertilizers and pesticides are considered.

Rice straw was excluded from the agriculture phase, and no allocation criteria had to be employed in this regard as most of the rice straw is burned in site and their emission is considered neutral (Williams et al. 2006). Hence byproduct, straw, has been omitted from the system boundary. As the main function of the system under the study is rice paddy produced in the field, the functional unit selected is 1 kg of rice paddy produced at field. Delivery to the farm or supermarket is also outside the set system boundary.

Data sources

The data for the life cycle inventory were obtained from different sources. On site records of what fertilizers and pesticides are applied as well as average working hours of machineries and their fuel consumption were obtained through interviews with farmers of different farm locations aforementioned. Personal communication with rice

Fig. 3 System boundary for this study



agriculture scientific research officer as well as specific literature (Basak 2010) provided typical amount of fertilizers that are applied during agricultural process. The machineries used were mostly retrieved from established factsheet produced by BBS (2012). Information of pesticides were taken from literature data by authors Dasgupta (2003) and Parveen and Nakagoshi (2001), and cited accordingly. Data for greenhouse emissions (methane), were taken from literature study (Khan and Saleh 2015), which are in par with agricultural LCA methodology and guidelines (Nemecek et al. 2014). Water use figure was used from literature (Chowdhury 2010), which stated average water usage; from which water consumption and emission were calculated using the guidelines (Nemecek et al. 2014). For the inputs where there were limited supporting data to conduct calculation, proxy values were used. The proxy values for ammonia, field emissions were taken from ecoinvent database[2], under the life cycle inventory of rice paddy production in India. Background data for all upstream activities of relevant inputs were taken from ecoinvent database 3.3 (Table 2).

Inventory analysis

This section will explain what data were collected, and how they were adapted to the LCA model to carry out the analysis using openLCA version 1.6 and ReCiPe's midpoint methodology (Huijbregts et al. 2017). Assumptions made and proxy data taken are mentioned here.

Field operation

Field operation include ploughing, fertilizing, irrigating with diesel powered pumps, sowing, application of plant protection products and harvesting. The types of machineries used were retrieved from Bangladesh Rice Research Institute's factsheet and Bangladesh Rice Agriculture Statistics (BBS 2012). The entries were made using ecoinvent database version 3.3, which included the manufacturing data of each machineries. The values entered were adapted from considering average working hours and fuel consumption, obtained

---

[2] Ecoinvent is the world's leading LCI database which delivers both in terms of transparency and consistency. The ecoinvent database provides a well-documented process data for a large number of products to help make informed choices.

Table 2 Paddy rice production phases and data sources

Phase	Subsystem	Sources of foreground data	Source of background data
Step by step rice paddy production process		Interview with farmers Rice Research Senior Scientific Officer	Ecoinvent database v3.3
Agricultural process	Mechanical field operations	Literature data (BBS 2012) Interview with farmers	Ecoinvent database v3.3
	Fertilizers	Rice Research Senior Scientific Officer Literature data (Basak 2010)	Ecoinvent database v3.3
	Pesticides	Literature data (Dasgupta 2003; Parveen and Nakagoshi 2001) Interview with farmers	Ecoinvent database v3.3
	Irrigation	Literature data (Chowdhury 2010)	Ecoinvent database v3.3
	Field emission	Literature data (Khan and Saleh 2015) Proxy data from India's Ecoinvent dataset used	Ecoinvent database v3.3
	Seeds	Interview with farmers Rice Research Senior Scientific Officer	Ecoinvent database v3.3
	Capital goods	Ecoinvent database v3.3	

Table 3 LCI of rice paddy production: model entries for field operation and manufacturing

Field process	Database entry	Quantity (ha)	Source
Ploughing	Tillage, ploughing	1	Interview with farmers
Fertilizing	Fertilising, by broadcaster	2	
Harvesting	Combine harvesting	1	
Application of plant protection products	Application of plant protection, by field sprayer	5	

Table 4 Model entries for fertilizers and sources

Commercial name	Ecoinvent database entry	Quantity (kg/ha)	Source
Urea (N)	Urea, as N	247.11	Literature data (Basak 2010) BRRI factsheet (BRRI 2017)
Triple-superphosphate (TSP)	Phosphate fertilizer, as P_2O_5	98.84	BRRI factsheet (BRRI 2017)
Muriate of potash (MOP)	Potassium chloride fertilizer, as K_2O	123.56	BRRI factsheet (BRRI 2017)
Gypsum	Gypsum	111.20	BRRI factsheet (BRRI 2017)
Organic fertilizer	Manure, solid, cattle	2471	Crosschecked with interview with farmers
Zinc	Zinc monosulfate	19.77	Crosschecked with interview with farmers
Potassium	Potassium sulphate, as K_2O	120	BRRI factsheet (BRRI 2017)

from interviewing farmers in the field survey conducted in Meherpur and Baliakandi farms in Bangladesh (Table 3).

Fertilizers

The use of different types and amount of fertilizer can vary to a great extent from one farm to another, especially of different regions of the country. Application also depends on the rice species and soil. The average use of fertilizers was estimated using a factsheet provided by senior scientific officer at Bangladesh Rice Research Institute as well as literature data (Basak 2010). The data was substantially similar when cross checked by personally communicating with rice farmers. There are naturally variation in quantity of application, from farm to farm, however, the variations were not considered typical and hence only the general prescribed amount is considered. The manufacturing processes (background system) were taken from ecoinvent database version 3.3 (Table 4).

Pesticide

As the use of pesticide vary from farm to farm in Bangladesh, data from two sources were used to model the LCA

Table 5 Model entries for pesticides

Commercial name	Class	Active ingredient	Chemical class in Ecoinvent	Source 1 (kg/ha)[a]	Source 2 (kg/ha)[b]
Basudin	Organophosphate	Diazinon	Organophosphorous	5.35	–
Cymbush	Pyrethroid	Cypermethrin	Pyrethroid compound	–	3.74
Sunfuron	Carbamate	Carbafuran	Carbamate compound	4.13	–
Supercolor	Benzimidazole	Carbendazim	Benzimidazole-compound	–	5.48
Dimecron	Organophoshate	Phosmadinon	Pesticide, unspecified	–	4.23

[a] Dasgupta (2003)

[b] Parveen and Nakagoshi (2001)

Table 6 Irrigation input and water emission

Water balance	Quantity (m^3/ha)	Source/methodology
Irrigation (withdrawal)	11,500	Chowdhury (2010)
To air (ET_{irr})	5175	WFLDB-guidelines
To surface water	4654.4	WFLDB-guidelines
To ground water	1163.6	WFLDB-guidelines
Equations and coefficients used		
Surface irrigation efficiency coefficient (EF_{irr})	0.45	
Evapotranspiration (to air)	0.45 × input irrigation water	
Emission to surface water	0.8 × ((ETirr /EFirr) − ETirr − water content of crop)	
Emission to ground water	0.2 × ((ETirr /EFirr) − ETirr − water content of crop)	

(Parveen and Nakagoshi 2001; Dasgupta 2003). Bangladeshi farmers have been recorded to use several classes of pesticides, herbicides and fungicides over the years, hence the most widely used pesticides based on interviewing farmers, were selected. According to the active ingredients, inventory data from ecoinvent were appropriately selected for the model (Table 5).

Irrigation

Irrigation in Bangladesh can be intensive. According to literature data, average irrigation requirement is 11,500 m^3/ha for one harvest (Chowdhury 2010). Water consumption was calculated using blue water consumption method, stated in the guideline for agricultural LCA (Nemecek et al. 2014). Green water (precipitation, moist) etc. were not considered as they do not have any tax on the environment. Water emissions were based on the equations provided in the same guidelines (Table 6).

Emissions from rice paddy field

Field emissions include direct air emissions of methane, nitrous oxide and ammonia, as well as emissions of phosphorous and nitrates to water. Anaerobic decomposition of organic matter and the consequent methane production are caused by intense water management practices because rice production hinges on long submersion times. This is however magnified with the use of fertilizers (Watanabe et al. 1995; Butterbach-Bahl et al. 1997; Mitra et al. 1999; Dan et al. 2001; Majumdar 2003; Harada et al. 2007; Arunrat and Pumijumnong 2017).

Carbon dioxide emissions were calculated using the instructions set in the world food life cycle database guideline, which is calculated on the basis of Urea applied as input during cultivation process. Methane emission were directly adopted from case study conducted in Bangladesh, where greenhouse gas emission in rice paddy field was calculated using IPCC guidelines (Khan and Saleh 2015). Since this methodology is also prescribed in the WFLDB-guidelines, which is used to model LCA of agricultural crops, the result of methane emission from paddy field was directly usable.

Because of lack of literature data and case studies, values for nitrogen dioxide and ammonia emission for the LCA model were adapted from ecoinvent database. Emissions from India's rice paddy production dataset was used as proxy, given the regional similarities, it served as the best proxy for this case study's purpose (Table 7).

Table 7 Emission to air from rice paddy field; data and sources

Field emission (air)	Quantity (kg/ha)	Methodology/source
Methane	133.28	IPCC guideline, WFLDB-guidelines (Nemecek et al. 2014) Calculated value (Khan and Saleh 2015)
Carbondioxide, fossil	387.96	WFLDB-guidelines Ecoinvent agriculture guideline Urea (kg):CO_2 (kg) = 1:1.570
Nitrogen dioxides	5.38	Proxy: India dataset—2013, EEA, EMEP/EEA air pollutant emission inventory guidebook 2013
Ammonia	31.49	Proxy: India dataset—2013, EEA, EMEP/EEA air pollutant emission inventory guidebook 2013

Table 8 Phosphorous emission to water

Emission	Quantity (kg/FU)	Source
Phosphorous to surface water	0.061069	Proxy: India dataset from Ecoinvent
Phosphate to ground water	0.21573	

Table 9 Carbon uptake data entry

Dataset entry	Quantity (kg/FU)	Methodology
Carbon dioxide, in air	0.41325	C content of biomass is almost always found to be between 45 and 50% (by oven-dry mass) Calculated using—http://www.fao.org/forestry/17111/en/ WFLDB-guidelines

Phosphorous releases

Phosphorous releases were adapted from dataset of India, retrieved from ecoinvent database to serve as proxy due to lack of literature studies and cases covered in Bangladesh. According to the guidelines to create the life cycle inventory for agricultural products, phosphorous emissions can be calculated using set of equations and variables, however, because of inadequate information to carry out the complete methodology, proxy data had to be used in this regard, from ecoinvent dataset of India's rice paddy production (Table 8).

Carbon uptake by crop from air

During growth of crops, the plants uptake carbon dioxide from air. This has to be taken into account for a precise analysis. This was calculated using the instructions set in WFLDB guidelines. Carbon content of biomass was assumed to be 47.5% (Table 9).

Land transformation due to land use

Land transformation is a change from one type of land to another due to anthropogenic use. The amount of land transformed is the area required to produce one unit of the functional unit of a product. In the case of this study, the functional unit is 1 kg of rice produced in 1 ha area of land. Hence the entries for land use change were entered according to this guideline (Nemecek et al. 2014) (Table 10).

Table 10 Entries for land use change

Database entry	Quantity (m^2)	Methodology
Transformation, from annual crop	2.5641025641	Occupied land:yield WFLDB-guidelines
Transformation, to annual crop	2.5641025641	

Seed production

According to the average data from the Bangladesh Rice Research Institute's factsheet, farmers use varying amount of seed per hectare area, on the basis of the cultivar used. For high yielding cultivar variety, often lower quantity of seed is required. The amount also varies by region, as different farming fields have to apply different amount to obtain optimum yield. Personal communication with rice research senior officer revealed that farmers are typically prescribed to apply 40 kg of rice seed per hectare. Interviews with farmers that was carried out in field survey stage revealed that as a general practice, seeds more than 40 kg (up to 60 kg) is applied depending on farmer's financial ability and resource availability. Hence an average of 50 kg/ha was considered as the typical seed input. Data for manufacturing of the seed

Table 11 ReCiPe impact indicators and impact result

Name	Impact result	Unit
Terrestrial acidification—TAP100	0.0273	kg SO_{2eq}
Human toxicity—htpinf	1.14918	kg 1,4-DCB_{eq}
Ionising radiation—IRP_HE	0.11827	kg $U235_{eq}$
Fossil depletion—FDP	0.68221	kg oil_{eq}
Terrestrial ecotoxicity—tetpinf	0.0011	kg 1,4-DCB_{eq}
Metal depletion—MDP	0.21115	kg Fe_{eq}
Ozone depletion—odpinf	1.39E-07	kg CFC-11_{eq}
Particulate matter formation—PMFP	0.01598	kg $PM10_{eq}$
Natural land transformation—NLTP	0.00031	M^2
Photochemical oxidant formation—POFP	0.01088	kg NMVOC
Marine eutrophication—MEP	0.01545	kg N_{eq}
Freshwater ecotoxicity—fetpinf	0.04642	kg 1,4-DCB_{eq}
Climate change—GWP100	3.15453	kg CO_{2eq}
Agricultural land occupation—ALOP	1.36268	M^2a
Urban land occupation—ULOP	0.05865	M^2a
Marine ecotoxicity—metpinf	0.03768	kg 1,4-DCB_{eq}
Water depletion—WDP	2.96767	M^3
Freshwater eutrophication—FEP	0.00122	kg P_{eq}

are taken from ecoinvent database. The LCA model included use of electricity for drying, and storage purpose. The model did not include transportation as the seed are manufactured domestically, and do not have significant distance from the farm gates.

Results and discussions

The results presented in this chapter are based on a functional unit defined as production of 1 kg of rice paddy.

Life cycle impact assessment and interpretation

The impact assessment phase was carried out by analyzing the results of the inventory in order to calculate the impact indicators detailed in previous section. Table 11 shows the indicators and the impact result of the LCA model for rice paddy production in Bangladesh. Some significant impact indicators are talked about in details in following sub sections.

Climate change as GWP100

As it can be seen in the table, to produce 1 kg of paddy rice, including all the inputs within the system boundary, the GWP_{100} indicator shows a carbon dioxide equivalent emission of approximately 3.15 kg per functional unit. This value represents the greenhouse gas emission, which is an aggregation of indirect and direct greenhouse emissions leading up to the production of paddy rice at each steps of its life cycle, and not only the greenhouse gas emission that is emitted directly from the paddy field.

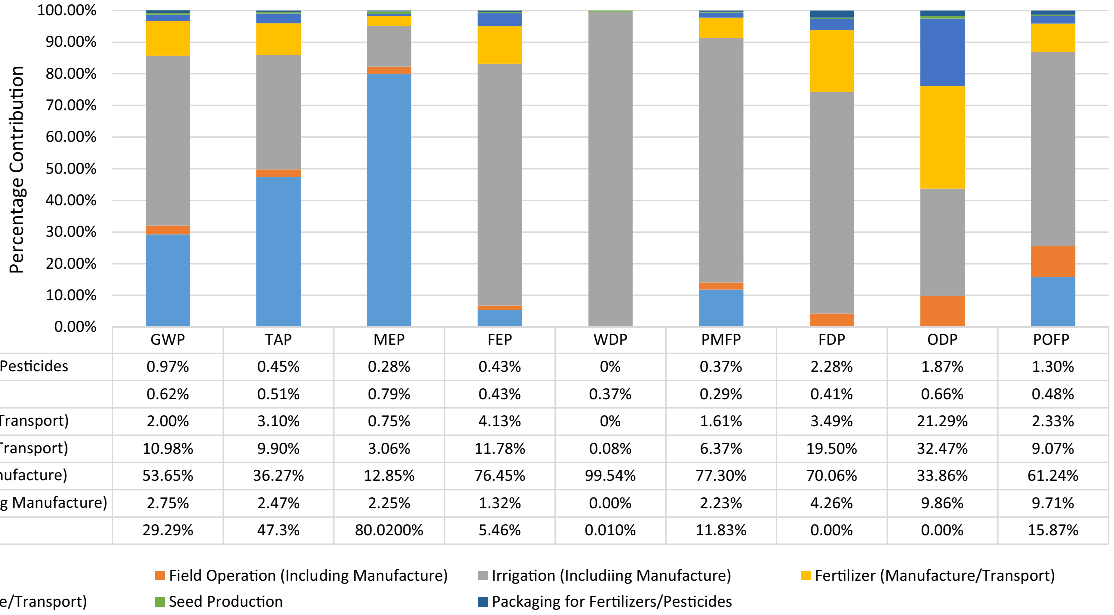
Kasmaprapruet et al. (2009) reported an almost similar global warming emission of 2.9 kg CO_{2eq} per functional unit (per kg of milled rice produced after dehusking). However, background system was not considered as the upstream activities started from cultivation process. Moreover, the emission may be overestimated, as it is unclear if the authors accounted for allocation criteria for milled rice produced, and by product of husk produced as a result.

Case study in Italy revealed that delivery of 1 kg of exported white milled rice from the farm under study, contributed a carbon dioxide equivalent emission of 2.9 kg (Blengini and Busto 2009). But in this case study, producing 1 kg of paddy rice emits more than 3.15 kg CO_{2eq}. The difference can be explained by mentioning the farm in Italy has non mechanized irrigation system, which has zero contribution to global warming potential; as there is no diesel combustion, or the need to use powered pumps. Their yield in 1 ha was also considered very high (7 t/ha). Due to which emission per functional unit is significantly lower. This makes a valid case in point, that to optimize the environmental load and production, maintaining high yield is necessary to obtain a low impact per functional unit generated.

Overall, the global warming impact during cultivation is largely due to methane emission from rice paddy field (29.29%) (Fig. 4). To reduce methane emissions from paddy fields, the options include using enhanced rice production technology such as minimizing the use of green manure and substituting pre-fermented compost from farm residues, adding nitrate or sulfate containing nitrogen fertilizer to suppress methane gas production or; change rice cultivation practices (Alting et al. 1997).

Photochemical oxidant formation

Energy consumption determines the impacts for photochemical oxidant formation. Non-methane volatile organic compounds (NMVOC) emission of magnitude 0.0123 kg per functional unit is the result (Table 11). The main source of NMVOC is from fuel combustion, particularly from field operation and road transport, according to emission inventory of NMVOC from anthropogenic sources, a case study conducted in China (Wei et al. 2008). In case of paddy rice production in Bangladesh, a contribution analysis reveals that irrigation system contributes 61.24% of photochemical oxidant formation, approximately 10% comes from field operation by machineries and 16% from paddy field emission (Fig. 4). Some NMVOCs damage the ozone layer in the upper atmosphere, and are also toxic for human health (European Environment Agency 2010). With the consequences in



	GWP	TAP	MEP	FEP	WDP	PMFP	FDP	ODP	POFP
■ Packaging for Fertilizers/Pesticides	0.97%	0.45%	0.28%	0.43%	0%	0.37%	2.28%	1.87%	1.30%
■ Seed Production	0.62%	0.51%	0.79%	0.43%	0.37%	0.29%	0.41%	0.66%	0.48%
■ Pesticide (Manufacture/Transport)	2.00%	3.10%	0.75%	4.13%	0%	1.61%	3.49%	21.29%	2.33%
■ Fertilizer (Manufacture/Transport)	10.98%	9.90%	3.06%	11.78%	0.08%	6.37%	19.50%	32.47%	9.07%
■ Irrigation (Includiing Manufacture)	53.65%	36.27%	12.85%	76.45%	99.54%	77.30%	70.06%	33.86%	61.24%
■ Field Operation (Including Manufacture)	2.75%	2.47%	2.25%	1.32%	0.00%	2.23%	4.26%	9.86%	9.71%
■ Field Emission	29.29%	47.3%	80.0200%	5.46%	0.010%	11.83%	0.00%	0.00%	15.87%

Fig. 4 Contribution of subsystems to different impact categories of rice paddy productions

mind, we can prioritize on the basis of contribution from each subsystem, and improve the rice production system in Bangladesh by replacing traditional operational tools with environmentally friendlier options.

Terrestrial acidification as TAP100

Impact assessment reveals 0.02827 kg SO_{2eq} is the resulting output per functional unit (Table 11). 47.3% of the impact is contributed from paddy field emission (Fig. 4). Some studies state that use of fertilizers type and timing of the application can determine the emissions of NH_3 (affecting acidification) (i Canals et al. 2006). Hence to mitigate this impact, further research needs to be conducted for precise contributions of terrestrial acidification by varying the types of fertilizers and their timing, to reach a sustainable rice production practice.

Water depletion

Direct use of water appears to be particularly intense, almost 3 m^3 of water per 1 kg of paddy rice produced is depleted; an indication that irrigation efficiency must be increased in order to optimize water depletion for rice agriculture. Currently, Bangladesh's standard irrigation practice is flooding the surface in most cases. This has an efficiency factor of only 0.45 (Nemecek et al. 2014). Perhaps, by employing sprinkler irrigation system or drip channeling as the standard practice, the extracted water can be more efficiently applied to all range of agricultural crops. The predicted trend of such a change can result in much less requirement of direct use of water.

Marine eutrophication and freshwater eutrophication

Eutrophication is the impact on ecosystems from substances containing nitrogen or phosphorous. The consequences of which, is growth of algae or plants resulting the occurrence of situation without oxygen in the bottom strata due to increased algal growth (Alting et al. 1997). Paddy field emission has the most dominating contribution to marine eutrophication (80%) (Fig. 4), with a total magnitude of 0.01588 kg N_{eq} (Table 11). Whilst irrigation system contributes the most to freshwater eutrophication (76%) with a total magnitude of 0.00126 kg P_{eq}.

Ozone depletion

Ozone depletion is majorly contributed by production of pesticide, fertilizers, machine operations in the field and transportation. Irrigation system also makes up 34% of the total impact magnitude of 0.159 mg CFC-11_{eq}. Blengini and Busto (2009) reported 0.10 mg CFC-$11_{eq,}$ although this magnitude was for every kg of milled rice delivered. It is clear that paddy rice production alone, is more environmentally burdening in Bangladesh.

Contribution analysis

A contribution analysis has been carried out with respect to the life cycle impact assessment result obtained for the production of 1 kg of paddy rice.

Figure 4 can hence be helpful to appraise the role and significance of the different subsystems that contribute to the life cycle impacts of paddy rice production. From this figure, it is possible to get a comprehensive and quick "at-a-glance" idea of the greatest contributor to different categories of impact indicators; on the basis of the inputs made in the inventory phase.

Global warming is mainly influenced by emissions from the paddy field (29.29%), which can be attributed to have been magnified by high usage of synthetic fertilizers and pesticides. Intense irrigation due to the amount of water withdrawal and machineries produced to facilitate the process means the highest percentage of contribution in global warming have come from irrigation (53.65%). Irrigation process also has great impact on three other indicators (FEP, PM, FD). This is unlike the irrigation system in Italy, which uses complete non-mechanized system called drip irrigation employing complex water canals and gravity to efficiently irrigate their rice paddy field. This neither consumes resources, nor puts an environmental burden (Blengini and Busto 2009). Their study stated that the irrigation subsystem has no contribution to global warming, ozone depletion, acidification or eutrophication. Our contribution analysis also reveals that significant contributions to climate change result from fertilizer use (10.98%).

As expected, water depletion is dominated by irrigation (99.54%). The remaining fractions being used by seed production, fertilizer production and field operation. Uses in packaging, and other inputs are almost negligible.

Paddy field emissions have the greatest impact on terrestrial acidification (47.3%). Highly affected by fertilizer emissions, the type of fertilizer used and the timing of the application determine the emissions of NH_3. The importance of LCA is automatically highlighted here as it can be a great tool to assess the best crop management options in terms of environmental performance. From the paddy field, marine eutrophication (78.20%) as well as emission of particulate matter (11.48%) is also considerably high. Perhaps this result emphasizes the need for further reliable and site specific data, opening windows of opportunity for excellent research, to develop a more sustainable agricultural practice to mitigate the field emissions.

It should be stated that fertilizer production has an immense impact on ozone depletion, contributing the highest for this indicator (32.47%). Fertilizers also have significant contributions to GWP (10.98%) and freshwater eutrophication (11.78%).

Field operation's contribution to each category indicator is noticeable (Fig. 4). As the primary source of their operation and maintenance is nonrenewable resources such as diesel, it is no surprise that they have remarkable contribution to photo chemical oxidant formation indicator (9.71%), ozone depletion (9.86%) and fossil depletion (4.26%). They also make up a noteworthy percentage of other impact categories.

From the figure (Fig. 4) it is evident that the "criminals" in the defined system boundary for the study are the irrigation process, manufacture of synthetic fertilizers and pesticides and emissions to air taking place in the rice paddy field (field emission) during the growth period; therefore, establishing the environmental hotspots in the system.

Impact magnitude and the need to identify acceptable limits

The impact analysis highlights the great potential of LCA, which can account for a large number of parameters and calculate complex production systems where both natural and industrial processes exist (Blengini and Busto 2009). However, while there is no set standard limit of the impact magnitude of rice production for each impact categories, it is hard to identify if the impact values obtained can be considered acceptable or not. Upon comparing results with case studies done on different geographic region, it can only emphasize the need to improve on those benchmarks. However, further research need to be conducted to find the global average of impact magnitude to better understand the range of impact value, which can be considered acceptable, and the magnitude which are beyond acceptable limits.

Perhaps this study can shed lights on the need of such a standard framework to develop good agricultural practice. Introduction of such policy will ensure standard and sustainable cultivation practice is maintained, to keep all impact indicators involved in agricultural crop production within acceptable limits. LCA can pave the way for such sustainable development, as its ability to account for large number of parameters is evidence, that a framework can be developed around its methodology which will be both holistic and robust.

Limitations of conducting LCA in developing country

A large volume of data is required to carry out LCA (Finkbeiner et al. 2014). This makes it especially challenging to conduct an LCA case study in developing country like Bangladesh. Data mining in Bangladesh can be very difficult and time consuming. Low standards of bookkeeping, administrative coverage and social performance means databases or archives do not have the best form of maintenance. Specific local literature are also outdated, have questionable reliability, or are not technically sound to provide the robust information required to maintain precision in the assessment.

Conclusion

The study shows that usage of fertilizers, pesticides and non-renewable resources generate a significant share of impact across all categories. It is clear that application of different products for crop management and cultivation practice affects the LCA results, thus using petrol, diesel or electricity as an energy source magnifies the emission of CO_2, NO_x, SO_x, heavy metal emission etc. Different fertilizers, pesticides have very different emission patterns due to their characteristics as well as different specific toxicities and manufacturing methods. Hence LCA may be used to guide the selection of these inputs with the aim of reducing environmental impacts. Greener technology such as drip irrigation system, solar irrigation system can be implemented at a large scale.

An analysis of improvement scenarios has shown that although mitigation solutions can be reached through an organic farming method, which does not involve application of commercial fertilizers such as urea, solutions cannot be restricted to single life steps or limited aspect. Since the consequences on the subsequent life phases could dramatically reduce or cancel out the improvements; such as reduction of yield. However, use of more environmentally benign pesticide and fertilizer compounds must be promoted.

Nevertheless, this LCA study attempted an objective environmental audit of the environmental system by quantifying emissions at a system level, in an effort to identify environmental hotspots of production. The original hypothesis was in fact correct, as the environmental hotspots are the irrigation phase and agricultural emission from paddy field. Communication of these results to producers in the form of improvement opportunities would be a useful addition to changing producer behavior and reducing environmental emissions. The producers of agricultural crops will benefit from this by being able to optimizing their yield with minimum environmental impact. The consequences of the change will improve food safety, improve public perception of the products and encourage environmentally friendly practice in all industries.

In this context, it is imperative to link the LCA results and the socio-economical needs of producers. This is crucial for acceptance by the agricultural sector, for example, if producers see LCA as a tool for optimizing their operation and increasing competitiveness by facilitating communication with the rest of the supply chain, this reaction will be from a much positive standpoint. However, communicating the LCA results remain a topic for further research.

Modelling the life cycle of paddy rice is both demanding and work intensive. It involves a large number of agricultural and industrial processes. Although improvements and further research are necessary, mainly studies pertaining to direct field emissions of nitrogen dioxide and ammonia in Bangladesh rice paddy production are of utmost importance. The present research has supplied quantitative results and information that might be useful in the future investigations.

References

Alting L, Hauschild M, Wenzel H (1997) Environmental assessment in product development. Philos Trans R Soc Lond A Math Phys Eng Sci 355(1728):1373–1388

Andersson K, Ohlsson T, Olsson P (1998) Screening life cycle assessment (LCA) of tomato ketchup: a case study. J Clean Prod 6(3):277–288

Anton A, Montero JI, Munoz P, Castells F (2005) LCA and tomato production in Mediterranean greenhouses. Int J Agric Resour Gov Ecol 4(2):102–112

Arunrat N, Pumijumnong N (2017) Practices for reducing greenhouse gas emissions from rice production in Northeast Thailand. Agriculture 7(1):4

Ayres RU, Ayres L (2002) A handbook of industrial ecology. Edward Elgar Publishing, Cheltenham

Basak J (2010) Fertilizer Requirement for Boro Rice Production in Bangladesh. Unnayan Onneshan-The Innovators. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjFosXYoYDUAhXIuo8KHbA-BeMQFggmMAA&url=http%3A%2F%2Fwww.unnayan.org%2Freports%2FLivelihood%2FFertilizer_Requirement_for_Boro_Rice_Production_in_Bangladesh.pdf&usg=AFQjCNG6aEwJ6v_mefBY9pASwQodqxQqrg&sig2=nqWHAOSy1dIVlFgZplGdew

BBS (2012) Yearbook of agricultural statistics. Bangladesh Bureau of Statistics, Bangladesh

Bennett R, Phipps R, Strange A, Grey P (2004) Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: a life-cycle assessment. Plant Biotechnol J 2(4):273–278

Blengini GA, Busto M (2009) The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J Environ Manag 90(3):1512–1522. http://dx.doi.org/10.1016/j.jenvman.2008.10.006

Breiling M, Tatsuo H, Matsuhashi R (1999) Contributions of rice production to Japanese greenhouse gas emissions applying life cycle assessment as a methodology. Tokyo, Laboratory for Land Resource Sciences, Department of Biological and Environmental Engineering, Graduate School for Agriculture and Life Sciences, The University of Tokyo, 32. http://www.breiling.org/publ/lcaricejap-en.pdf. Accessed 25 May 2017

Brentrup F, Küsters J, Lammel J, Barraclough P, Kuhlmann H (2004) Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. Eur J Agron 20(3):265–279

Brodt S, Kendall A, Mohammadi Y, Arslan A, Yuan J, Lee IS, Linquist B (2014) Life cycle greenhouse gas emissions in California rice production. Field Crops Res 169:89–98

BRRI (2017) Bangladesh rice knowledge bank: a dynamic source of rice knowledge. http://knowledgebank-brri.org/. Accessed 16 May 2017

BRRI and BBS (2016) Rice export data. Bangladesh Rice Research Institution, Dhaka. http://data.gov.bd/dataset/export-and-import-rice-data-bangladesh. Accessed 25 May 2017

Butterbach-Bahl K, Papen H, Rennenberg H (1997) Impact of gas transport through rice cultivars on methane emission from rice paddy fields. Plant Cell Environ 20(9):1175–1183

Charles R, Jolliet O, Gaillard G, Pellet D (2006) Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agric Ecosyst Environ 113(1):216–225

Chowdhury NT (2010) The relative efficiency of water use in Bangladesh agriculture. Q J Int Agric 49(2):147–164

CIA (2017) The world factbook. Central Intelligence Agency, USA. https://www.cia.gov/library/publications/resources/the-world-factbook/. Accessed 25 May 2017

Consoli F, Allen D, Boustead I, Fava J, Franklin W, Jensen AA, de Oude N, Parrish R, Perriman R, Postlethwaite D, Quay B, Sieguin J, Vigon B (eds) (1993) Guidelines for life cycle assessment. A code of practice. SETAC Press, Pensacola

Dan J, Krüger M, Frenzel P, Conrad R (2001) Effect of a late season urea fertilization on methane emission from a rice field in Italy. Agric Ecosyst Environ 83(1):191–199

Dasgupta S (2003) Bangladesh pesticide use (Survey Data No. wps3776). World Bank. http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/0,,contentMDK:22302556~pagePK:64214825~piPK:64214943~theSitePK:469382,00.html. Accessed 25 May 2017

de Miranda MS, Fonseca ML, Lima A, de Moraes TF, Rodrigues FA (2015) Environmental impacts of rice cultivation. Am J Plant Sci 6(12):2009

European Environment Agency (2010) Non-methane volatile organic compounds (NMVOC) emissions [indicator specification]. https://www.eea.europa.eu/data-and-maps/indicators/eea-32-non-methane-volatile-1. Accessed 22 June 2017

FAO (2011) Looking ahead in world food and agriculture: perspectives to 2050. Food and Agriculture Organization, Italy. http://www.fao.org/docrep/014/i2280e/i2280e.pdf. Accessed 25 May 2017

FAO (2017) FAOSTAT. http://www.fao.org/faostat/en/#country/16. Accessed 23 May 2017

Finkbeiner M, Ackermann R, Bach V, Berger M, Brankatschk G, Chang YJ, Grinberg M, Lehmann A, Martínez-Blanco J, Minkov N, Neugebauer S, Scheumann R, Schneider L.Wolf K (2014) Challenges in life cycle assessment: an overview of current gaps and research needs. In: Background and future prospects in life cycle assessment. Springer, Dordrecht, pp 207–258. http://dx.doi.org/10.1007/978-94-017-8697-3_7

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Penington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91(1):1–21

Garnett T (2011) Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)?. Food Pol 36:S23–S32. http://dx.doi.org/10.1016/j.foodpol.2010.10.010

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1. https://www.researchgate.net/profile/Mark_Goedkoop/publication/230770853_Recipe_2008/links/09e4150dc068ff22e9000000.pdf. Accessed 25 May 2017

Goossens Y, Geeraerd A, Keulemans W, Annaert B, Mathijs E, De Tavernier J (2017) Life cycle assessment (LCA) for apple orchard production systems including low and high productive years in conventional, integrated and organic farms. Agric Syst 153:81–93

Haes HAU (2002) Industrial Ecology and life cycle assessment. In: Handbook of industrial ecology. Edward Elgar, Cheltenham, pp 138–148

Haes HAU (2004) Life-cycle assessment and developing countries. J Ind Ecol 8(1–2):8–10

Harada H, Kobayashi H, Shindo H (2007) Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: life-cycle inventory analysis. Soil Sci Plant Nutr 53(5):668–677

Hatcho N, Matsuno Y, Kochi K, Nishishita K (2012) Assessment of environment-friendly rice farming through life cycle assessment (LCA). CMU. J Nat Sci 11. http://rac.oop.cmu.ac.th/editcmuj/sites/default/files/pdf/NaturalSciences/Volume%2011,%20Number%201,%20Special%20Issue%20on%20agricultural%20natural%20resources/054%20Journal%202012-2.pdf. Accessed 25 May 2017

Hokazono S, Hayashi K (2015) Life cycle assessment of organic paddy rotation systems using land-and product-based indicators: a case study in Japan. Int J Life Cycle Assess 20(8):1061–1075

Hokazono S, Hayashi K, Sato M (2009) Potentialities of organic and sustainable rice production in Japan from a life cycle perspective. Agron Res 7(1):257–262

Hoque N (2012) Eco-friendly and organic farming in Bangladesh—international classification and local practice. Dissertation. Institut für Agrarsoziologie und Beratungswesen der Justus-Liebig-Universität Gießen, Germany. http://geb.uni-giessen.de/geb/volltexte/2013/8778/pdf/HoqueMdNazmul_2012_06_05.pdf. Accessed 25 May 2017

Huijbregts MA, Steinmann ZJ, Elshout PM, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. http://dx.doi.org/10.1007/s11367-016-1246-y

i Canals LM, Burnip GM, Cowell SJ (2006) Evaluation of the environmental impacts of apple production using life cycle assessment (LCA): case study in New Zealand. Agric Ecosyst Environ 114(2):226–238

Jiménez-González C, Kim S, Overcash MR (2000) Methodology for developing gate-to-gate life cycle inventory information. Int J Life Cycle Assess 5(3):153–159. http://dx.doi.org/10.1007/BF02978615

Kasmaprapruet S, Paengjuntuek W, Saikhwan P, Phungrassami H (2009) Life cycle assessment of milled rice production: case study in Thailand. Eur J Sci Res 30(2):195–203

Khan MRU, Saleh AFM (2015) Model-based estimation of methane emission from rice fields in Bangladesh. J Agric Eng Biotechnol. http://www.bowenpublishing.com/jaeb/paperInfo.aspx?PaperID=16903. Accessed 25 May 2017

Khush GS (2005) What it will take to feed 5.0 billion rice consumers in 2030. Plant Mol Biol 59:1–6. http://dx.doi.org/10.1007/s11103-005-2159-5

MacWilliam S, Wismer M, Kulshreshtha S (2014) Life cycle and economic assessment of Western Canadian pulse systems: the inclusion of pulses in crop rotations. Agric Syst 123:43–53. http://dx.doi.org/10.1016/j.agsy.2013.08.009

Majumdar D (2003) Methane and nitrous oxide emission from irrigated rice fields: proposed mitigation strategies. Curr Sci 84(10):1317–1326

Mattsson B, Wallén E (2003) Environmental life cycle assessment (LCA) of organic potatoes. Acta Hortic. International Society for Horticultural Science (ISHS), Leuven, pp 427–435. http://dx.doi.org/10.17660/ActaHortic.2003.619.51

McMichael AJ, Powles JW, Butler CD, Uauy R (2007) Food, livestock production, energy, climate change, and health. Lancet 370(9594):1253–1263. http://dx.doi.org/10.1016/S0140-6736(07)61256-2

Miettinen P, Hämäläinen RP (1997) How to benefit from decision analysis in environmental life cycle assessment (LCA). Eur J Oper Res 102(2):279–294. http://dx.doi.org/10.1016/S0377-2217(97)00109-4

Mitra S, Jain MC, Kumar S, Bandyopadhyay SK, Kalra N (1999) Effect of rice cultivars on methane emission. Agric Ecosyst Environ 73(3):177–183

Mogensen L, Kristensen T, Nielsen NI, Spleth P, Henriksson M, Swensson C, Hessle A, Vestergaard M (2015) Greenhouse gas emissions from beef production systems in Denmark and Sweden. Livest Sci 174:126–143

Mosleh MK, Hassan QK, Chowdhury EH (2015) Application of remote sensors in mapping rice area and forecasting its production: a review. Sensors 15(1):769–791

Muthayya S, Hall J, Bagriansky J, Sugimoto J, Gundry D, Matthias D, Prigge S, Moench-Pfanner R, Maberly G (2012) Rice fortification: an emerging opportunity to contribute to the elimination of vitamin and mineral deficiency worldwide. Food Nutr Bull 33(4):296–307

Muthayya S, Sugimoto JD, Montgomery S, Maberly GF (2014) An overview of global rice production, supply, trade, and consumption. Ann N Y Acad Sci 1324(1):7–14. http://dx.doi.org/10.1111/nyas.12540

Nemecek T, Bengoa X, Lansche J, Mouron P, Rossi V, Humbert S (2014) Methodological guidelines for the life cycle inventory of agricultural products, version 2.0, July 2014. World Food LCA Database (WFLDB). Quantis and Agroscope, Lausanne

Nemecek T, Jungbluth N, i Canals LM, Schenck R (2016) Environmental impacts of food consumption and nutrition: where are we and what is next? Int J Life Cycle Assess 21(5):607–620. http://dx.doi.org/10.1007/s11367-016-1071-3

Nie Z, Feng GAO, Gong X, Wang Z, Zuo T (2011) Recent progress and application of materials life cycle assessment in China. Progr Nat Sci Mater Int 21(1):1–11

Nienhuis IJ, de Vreede IP (1996) Utility of the environmental life cycle assessment method in horticulture. In: XIII international symposium on horticultural economics 429:531–538. http://www.actahort.org/books/429/429_69.htm. Accessed 25 May 2017

Notarnicola B, Hayashi K, Curran MA, Huisingh D (2012) Progress in working towards a more sustainable agri-food industry. J Clean Prod 28:1–8. http://dx.doi.org/10.1016/j.jclepro.2012.02.007

Notarnicola B, Tassielli G, Renzulli PA, Monforti F (2017) Energy flows and greenhouses gases of EU (European Union) national breads using an LCA (life cycle assessment) approach. J Clean Prod 140(Part 2):455–469. http://dx.doi.org/10.1016/j.jclepro.2016.05.150

OECD/FAO (2016) Agricultural outlook 2016–2025. OECD Publishing, Paris. http://dx.doi.org/10.1787/agr_outlook-2016-en

Önder M, Ceyhan E, Kahraman A (2011) Effects of agricultural practices on environment. Biol Environ Chem 24:28–32

Owen J (2005) Farming claims almost half Earth's land, new maps show. National Geographic News. http://news.nationalgeographic.com/news/2005/12/1209_051209_crops_map.html. Accessed 25 May 2017

Parveen S, Nakagoshi N (2001) An analysis of pesticide use for rice pest management in Bangladesh. J Int Dev Cooperation 8(1):107–226

Pelletier N (2014). Life cycle assessment in agriculture. Alberta Agriculture and Forestry, Canada, p. 32http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/sag15417/$FILE/LifeCycle-Assessment.pdf

Population Reference Bureau (2016) World population data sheet. Population Reference Bureau, Washington, p 22. http://www.prb.org/pdf16/prb-wpds2016-web-2016.pdf

Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt WP, Suh S, Weidema BP, Pennington DW (2004) Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ Int 30(5):701–720

Roy P, Shimizu N, Okadome H, Shiina T, Kimura T (2007) Life cycle of rice: challenges and choices for Bangladesh. J Food Eng 79(4):1250–1255

Roy P, Nei D, Okadome H, Nakamura N, Orikasa T, Shiina T (2008) Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. J Food Eng 86(2):225–233

Roy P, Nei D, Orikasa T, Xu Q, Okadome H, Nakamura N, Shiina T (2009) A review of life cycle assessment (LCA) on some food products. J Food Eng 90(1):1–10

Soussana JF (2014) Research priorities for sustainable agri-food systems and life cycle assessment. J Clean Prod 73:19–23. http://dx.doi.org/10.1016/j.jclepro.2014.02.061

The World Bank (2010) Employment in agriculture (% of total employment). http://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=BD. Accessed 25 May 2017

Tillman AM, Baumann H (2004) The Hitchhikers guide to LCA. Studentlitteratur AB, Lund

Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schlesinger WH, Simberloff D, Swackhamer D (2001) Forecasting agriculturally driven global environmental change. Science 292(5515):281–284. http://dx.doi.org/10.1126/science.1057544

Torrellas M, Antón A, López JC, Baeza EJ, Parra JP, Muñoz P, Montero JI (2012) LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int J Life Cycle Assess 17(7):863–875

Uddin MT, Takeya H (2006) Comparitives study on integrated farming in Bangladesh and other countries. Nagoya University. http://ageconsearch.umn.edu/bitstream/200194/2/Resear_03%20Vol-XXIX.pdf

USDA (2017). World agricultural production. https://apps.fas.usda.gov/psdonline/circulars/production.pdf

Van Woerden S (2001) The application of life cycle analysis in glasshouse horticulture. International conference LCA in foods, pp 136–140

Veisi H, Shomohammadi A, Khoshbakht K, Damghani A, Soltani E (2017) Life cycle assessment of potato production semi-mechanized method in Iran: a case study of Markazi province. Iran J Biosyst Eng 47(4):666–659

Watanabe A, Kajiwara M, Tashiro T, Kimura M (1995) Influence of rice cultivar on methane emission from paddy fields. Plant Soil 176(1):51–56

Wei W, Wang S, Chatani S, Klimont Z, Cofala J, Hao J (2008) Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China. Atmos Environ 42(20):4976–4988. http://dx.doi.org/10.1016/j.atmosenv.2008.02.044

Williams A, Audsley E, Sandars D (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities: Defra project report IS0205. Zu Finden. http://Randd.Defra.Gov.Uk/Default.Aspx. Accessed 25 May 2017

Yoshikawa N, Ikeda T, Amano K, Fumoto T (2012) Life-cycle assessment of ecologically cultivated rice applying DNDC-Rice model. In: 10th international conference on EcoBalance "Challenges and solutions for sustainable society", Yokohama. http://www.ritsumei.ac.jp/se/rv/amano/pdf/2012EBJ-yoshikawanaoki.pdf. Accessed 25 May 2017