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Environmental profile of rice production in Southern Brazil: A comparison between irrigated and subsurface drip irrigated cropping systems

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ABSTRACT

Agricultural activities in 2005 accounted for 10–12% of the total global anthropogenic emissions of greenhouse gases (GHGs) and the majority of N_2O and half of CH_4 emissions. Therefore, mitigating GHG emissions in agriculture is fundamental to reduce its share of responsibility for the global climate change. Rice (paddy) is the second most important commodity worldwide, and rice cropping fields significantly contribute to climate change since they are a considerable source of methane. In this study, improvements were made to several stages of the life cycle of the rice production system in Southern Brazil with the aim of mitigating environmental impacts, namely: 1) Cultivation, 2) Power generation, 3) Drying, 4) Milling, 5) Packaging, and 6) Transportation. This study was carried out from June 2012 to August 2013. The functional units adopted were 1 ha, 1000 kg of rice at the farm gate and 1000 kg of packed rice (5-kg net weight packs), available at retail. The system boundary covered field operations, including transportation after harvest, fertilizer production, power generation, packaging and transportation to the retailer. The results showed that the new rice production system (subsurface drip irrigated rice crop, among others improvements) significantly mitigates environmental impacts, particularly due to reduced water consumption (approximately 2800 m^3 t^{-1} packed rice at retail) and primary energy demand (approximately 6300 MJ t^{-1} packed rice at retail) as well as GWP (approximately 1200 kg CO_2-eq t^{-1} packed rice at retail), besides the benefit of increased yield (1150 kg rice at farm gate ha^{-1}). The new irrigation system accounted for most of these benefits. The entire rice production chain was improved, from farm to transportation and distribution to retail stores. The results indicated that changing the irrigation from the flooded system to the SSDI system was responsible for most savings, i.e. 50% less water consumption, 90% less electric power consumption, 30% less eutrophication, 66% less acidification, 66% lower GWP, not to mention 15% higher yield. The power plant based on rice husk combustion accounted for 498 MJ electric power exported to the grid and 129 kg silica produced from rice husk. The drying stage was responsible for using 254 MJ renewable energy from waste, thus saving 177 kg of firewood and recovering 16 kg of rice.

1. Introduction

Agricultural lands are responsible for approximately 40–50% of the Earth's land occupation and the estimated emissions from agricultural activities in 2005 were 5.1–6.1 Gt CO_2-eq yr^{-1}, which corresponds to 10–12% of the total global anthropogenic emissions of greenhouse gases (GHGs). 54% of this amount is due to methane emissions – CH_4, 3.3 Gt CO_2-eq yr^{-1}, while the remaining 46% is due to nitrous oxide emissions – N_2O, 2.8 Gt CO_2-eq yr^{-1}. Taking into account the global anthropogenic emissions in 2005, agriculture accounted for approximately 60% of N_2O and 50% of CH_4 emissions. Moreover, an annual emission increase of approximately 60 Mt CO_2-eq yr^{-1} on average was observed from 1990 to 2005

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(Smith et al., 2007).

Therefore, mitigation of GHG emissions in agriculture is fundamental for reducing its contribution to the global climate change. Among the options to face this challenge, the following stand out: improved cropland management, grazing land management/pasture improvement, management of organic soils, restoration of degraded lands, livestock management, manure/biosolid management and bioenergy (Smith et al., 2007).

Linquist et al. (2012) conducted a meta-analysis on 57 published studies that compared the global warming potential (GWP) of CH_4 and N_2O emissions from rice, wheat and maize. The results showed that the GWP of CH_4 and N_2O emissions from rice (3757 kg CO_2-eq ha^{-1} $season^{-1}$) were higher than the emissions from the other cereals (1399 kg CO_2-eq ha^{-1} $season^{-1}$ - maize and 662 kg CO_2-eq ha^{-1} $season^{-1}$ - wheat). Expressing these values per ton of grain, the yield-scaled GWP of rice (657 kg CO_2-eq t^{-1}) was approximately four times higher than that of maize (185 kg CO_2-eq t^{-1}) and wheat (166 kg CO_2-eq t^{-1}), which suggests greater opportunities for mitigation of rice production systems.

Rice (paddy) is the second most important commodity worldwide, with a production of 740,902,532 t in a harvested area of 165,163, 423 ha in 2013 (FAOSTAT, 2012). Brazil is the ninth largest rice producer worldwide; the production was 11,782,549 t in a harvested area of 2,353,152 ha in the 2013 crop (FAOSTAT, 2012). Rice production is located in the Brazilian states of Rio Grande do Sul, Santa Catarina and Mato Grosso. The irrigated rice cultivation practiced in Southern Brazil accounts for an average of 54% of the Brazilian rice production. Rio Grande do Sul state is Brazil's largest producer with a production of 7,933,400 t in a harvested area of 1,066,600 ha and an average yield of 7438 kg ha^{-1} (MAPA, n.d.; CONAB, 2013).

Rice cropping fields are gradually expanding worldwide, and they are expected to continue increasing as the world population grows. Besides its relevance for feeding people as the basis of meals in several countries, rice is also responsible for generating jobs and income to many people. However, rice cropping fields are significant contributors to climate change since they are a considerable source of methane.

Therefore, understanding the environmental performance of rice cropping systems as well as ways to mitigate methane emissions in these cropping systems is an important issue. For this reason, studies on rice production have been developed in several countries, such as Brazil (Bayer et al., 2014, 2015), China (Xue et al., 2014; Yi-hu et al., 2014), India (Gathorne-Hardy et al., 2013), Iran (Khoshnevisan et al., 2014; Mohammadi et al., 2015), Italy (Blengini and Busto, 2009; Fusi et al., 2014), Japan (Breiling et al., 2005; Harada et al., 2007; Hokazono and Hayashi, 2012, Hayashi et al., 2014; Katayanagi et al., 2016; Riya et al., 2015), Thailand (Kasmaprapruet et al., 2009; Perret et al., 2013; Thanawong et al., 2014), the USA (Brodt et al., 2014), and other countries.

Kasmaprapruet et al. (2009) applied LCA to milled rice production in Thailand. The estimated emission of GHG was 2.93 kg CO_2-eq kg^{-1} milled rice (at mill gate, unpacked), considering that 95% of the emissions were attributed to the cultivation stage and 43% of the GWP was due to methane emissions from the paddy rice. Acidification was estimated as 3.19 g SO_2-eq. kg^{-1} milled rice, with contribution mainly from the rice cultivation (51%) and from the drying process (42%). Eutrophication was estimated as 12.90 gNO_3-eq kg^{-1} milled rice, also with the main contributions from rice cultivation (81%) and drying process (17%). Therefore, the rice cultivation stage was found to have the highest environmental impact out of the three categories evaluated.

Blengini and Busto (2009) applied LCA to three rice farming and food processing methods in Northern Italy: organic farming, upland farming and parboiling (improvement scenarios). The authors modified the LCA model for the exported white milled rice (baseline scenario) with the aim of investigating the potential for improvement in environmental performance of the rice industry. The LCA results showed the following impact per kg of delivered white milled rice: emission of 2.9 kg CO_2-eq, primary energy consumption of 17.8 MJ and use of 4.9 m^3 of water for irrigation. The organic and upland farming had the potential to reduce the impact per unit of cultivated area. Nevertheless, the lower grain yields of both scenarios largely reduced the environmental benefits per kg of the final product in the case of upland rice production, and almost zeroed the benefits for organic rice.

Thanawong et al. (2014) developed a study on rice production in Northeastern Thailand in 2010 which evaluated 43 households as to three rice cropping systems, i.e.: wet-season rain-fed, wet-season irrigated, and dry-season irrigated systems. According to the authors, a wide range of performances and impacts were observed even though cropping practices were relatively homogeneous. The differences among the systems were predominantly due to differences in yield, which were largely impacted by the water supply. The GWP_{100} of the wet-season rainfed systems was 2.97 kg CO_2-eq. kg^{-1} rice against 4.87 kg CO_2-eq. kg^{-1} rice for wet-season irrigated and 5.55 CO_2-eq. kg^{-1} rice for dry-season irrigated systems. The results showed that the wet-season rainfed systems were more eco-efficient in most impact categories.

Khoshnevisan et al. (2014) applied LCA to assess the environmental performance of consolidated rice farms (CF) – farms that have been integrated to increase their mechanization index, and traditional farms (TF) – small farms with lower mechanization index, in Gilan Province, Iran. The two main reasons for the higher energy efficiency of CFs were: a) the total energy input in the CFs was lower than the energy input in the TFs, and b) the CFs employed better agricultural management, including the use of higher-yielding varieties of rice that produced higher yields. This meant that the CFs produced fewer environmental burdens per ton of rice. The electricity accounted for the greatest share of impact for both types of farms, followed by P-based and N-based chemical fertilizers.

The study developed by Fusi et al. (2014) in Italy for the years 2009–2013 had the goal of evaluating the environmental performance of flooded paddy rice cultivation with different types of straw management. The authors compared two scenarios that are a standard cultivation practice – the straw is incorporated into the soil after chopping, and an alternative scenario - the straw collected by baling is sold. The results showed that the environmental impact was mostly due to field emissions, the fuel consumed by mechanized field operations, and the drying of paddy rice. Regarding the two scenarios, straw collection enhances the environmental performance of rice production, excluding freshwater eutrophication. According to this study, solutions to reduce the use of fossil fuel, methane emissions as well as the emissions from fertilizers through leaching and volatilization should be applied in order to improve the environmental performance of rice production.

Brodt et al. (2014) conducted a study on GHG emissions of rice produced in California, USA. According to the results, the field emissions contributed 69% to the GWP_{100} which was estimated as 1.47 kg CO_2-eq. kg^{-1} of packed rice. These lower emissions per kg of rice in comparison to other rice producing regions were attributed to high grain yields associated to relatively low field methane emissions. Since field emissions prevail, the greatest opportunities to improve the environmental performance of rice production are reduction of field CH_4 emissions by means of different field management practices, optimization of N fertilizer use, and enhanced fuel efficiency or reduced use of farm machinery.

In Southern Brazil, flooded irrigated rice is grown in summer, and soil tillage operations that incorporate the rice and ryegrass residues into the soil are performed only in the spring season. Bayer et al. (2015) evaluated the hypothesis that moving the soil tillage from spring to the fall season might decrease yield-scaled GHG emissions during the summer rice season due to lower availability of C compounds in subsurface soil layers to methanogenic bacteria. The results showed that moving soil tillage from spring to fall could reduce CH_4 emissions by 24% from flooded rice systems, while no effect was observed on N_2O emissions and rice yields. The net effect was a 21% reduction in GWP and a 25% decrease in yield-scaled emissions, being 1.06 kg CO_2-eq kg^{-1} rice in the fall tillage compared to 1.41 kg CO_2-eq kg^{-1} rice in the spring tillage treatment. Therefore, the fall tillage is a viable alternative to mitigate yield-scaled GWP of flooded rice systems.

Methane emissions from rice crops can be mitigated via water management practices. According to a study developed in central Japan by Kudo et al. (2014), a compound treatment with a combination of flooding, midseason drainage and intermittent drainage might be an effective water management practice for mitigating GHG emissions while maintaining rice yield.

Minamikawa et al. (2016) tested the hypothesis that appropriate water management might mitigate the emission of methane from rice paddies at six field sites in central Thailand. The authors simulated CH_4 emission from a rice-rice double cropping system from 2001 to 2060 considering three water management practices: continuous flooding, single aeration and multiple aeration. The results showed that single aeration and multiple aeration mitigated CH_4 emission by approximately 22% and 55%, respectively, in comparison to continuous flooding, which were comparable to those from 2001 to 2010.

Haque et al. (2016) evaluated the influence of a 30-day midseason drainage practice on the GWP and GHG intensity and yields in comparison to those of continuously flooding rice cropping systems in the East monsoon. The results showed that midseason drainage reduced the GWP by 46–50% of the continuous flooding, mainly due to 50–53% reduction of seasonal CH_4 fluxes. On the other hand, midseason drainage increased N_2O flux by 20–37% over the continuous flooding, but the N_2O emission increase showed negligible influence on the GWP. Since both irrigation systems showed the same rice yield, midseason drainage could reduce GHG intensity by 50–56% of the continuous flooding.

On the other hand, water is critical for flooded rice cropping to ensure high grain yields. The amount of water required for rice cultivation is the sum of the water required to saturate the soil, the water to form the water layer, the water to replace evapotranspiration losses, the water to form plant tissues and to compensate for all losses in the water distribution system in the tillage. The flooded rice paddy has the advantage of increasing the availability of nutrients, helping in weed control and in the thermoregulatory effect of the water layer. Despite these advantages, continuous irrigation has disadvantages such as the large water demand and the possibility of migration of nutrients and pesticides to water bodies (SOSBAI, 2003).

Besides methane emissions, rice paddies cause other environmental impacts that should be considered as well.

Colpo et al. (2009) adopted the benthonic macroinvertebrate community as a bioindicator in order to compare quality of the water that drains from the flooded rice paddy – drainage water, versus the irrigation water sourced from Gravataí River, near Porto Alegre city. The study was carried out at the Rice Experiment Station of IRGA, in Cachoeirinha, Rio Grande do Sul, Brazil, during the 2006/2007 crop. A more complex and rich community was observed at the drainage channel than at the irrigation channel, which indicated that the water quality was better in the drainage water than at the irrigation points. Therefore, the cities and industries located in the neighborhood of Porto Alegre showed higher environmental impact due to water than rice crops managed according to technical guidelines.

In a survey of the chemical composition of water used to irrigate rice in Rio Grande do Sul state, Brazil, Macedo et al. (2001a, b) reported that concentrations of nutrients analyzed were below the levels considered as standard in Brazilian legislation and that drainage water from irrigated rice paddies did not contribute to change their original nutrient contents.

A study developed by Macedo and Menezes (2004) listed a set of irrigated rice crop management practices that could increase grain yield, improve efficiency of water usage and reduce the environmental impact of the activity. These management practices are as follows: systematization of the area, sowing time, early irrigation, availability of nutrients and fertilizers, preservation of the water layer, breaking off the irrigation and drainage for harvest.

As a consequence of the concerns about the environmental impact of industrial activities and packaging materials which have brought about many LCA studies since the turn of the millennium, assessing the environmental performance of agricultural activities has gained importance all over the world (Schau and Fet, 2008; Ruviaro et al., 2011; Bessou et al., 2013). Scientific approaches are necessary to assess the environmental profile of products in order to achieve a reliable communication with the public and to avoid greenwashing as well. With this concern, the “End-to-End Sustainability” project was developed by Walmart Brazil and its main suppliers with the purpose of showing that it is possible to develop more sustainable products and processes in large, medium and small companies (Walmart, 2013). A total of 18 products resulted from this project, which are available at Walmart stores in Brazil. These products include food (rice, mayonnaise, condensed milk, tomato sauce, soft drink and hamburger), besides personal care and cleaning products, among others.

Rice (160.3 g day^{-1}) and beans (182.9 g day^{-1}) are the basis of Brazilians' food consumption (IBGE, 2011). For that reason, rice was chosen as one of the products of the “End-to-End Sustainability” project. In this project, Pilecco Nobre Alimentos Ltda. implemented several improvements in the rice production chain with the aim of mitigating the environmental impact of the product with the assistance of the Institute of Food Technology - ITAL. Life cycle thinking was applied to the rice production system in order to evaluate possibilities of mitigating the environmental impact of rice fields.

The objective of this paper is to describe the environmental benefits obtained from the following improvements made to the rice production chain, in Alegrete, Rio Grande do Sul, Brazil: 1) subsurface drip irrigation (SSDI) of the rice cropping system; 2) rice husk used as electricity-generating fuel; 3) use of steam radiators and homogeneous temperature system to dry rice grains; 4) rice recovery after husk removal at the milling stage; 5) rice bags made of plastic from renewable resources and 6) use of diesel S10 and a more efficient truck fleet. The life cycle assessment was applied from a farm-to-retail perspective in order to quantify the environmental performance of the packed rice available at retail stores.

Moreover, this publication provides information about the environmental performance of a SSDI system, which does not exist in the literature.

2. Methods

Based upon the life cycle approach, improvements were made to cultivation, production of electricity, drying and packaging, as well as to the transportation and distribution stages of the rice production chain. The study was conducted taking into account the recommendations of the International Standards ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006).

2.1. Goal and scope definition

The goal of this study was to improve the environmental performance of rice production. Therefore, a critical evaluation was conducted throughout the life cycle of rice to detect opportunities for improvements.

The scope of this study was to evaluate the improvements of the rice production system of the BR IRGA 417 cultivar implemented by Pilecco Nobre Alimentos Ltda. in a 258-ha cultivation area in Alegrete, Rio Grande do Sul, Brazil. Alegrete is the largest municipality of Rio Grande do Sul, extending over 7804 km^2. It is situated 76 m above sea level (29° 47′ 5″ S, 55° 46′ 33″ W). The climate is subtropical, warm temperate, with well distributed rainfall and well-defined seasons. The average annual precipitation is 1500 mm and the average relative humidity is approximately 75%. Its average annual temperature is 19.1 °C.

The functional units adopted were 1 ha, 1000 kg of rice at farm gate and 1000 kg of packed rice (5-kg net weight packs), available at retail. The study was carried out from June 2012 to August 2013.

2.2. Description of the rice production systems evaluated

Rice cultivated in flooded paddy fields and sold in plastic bags was established as a baseline case against which the environmental impacts of the conditions could be quantified. The life cycle stages considered in this study as well as the improvements made along the rice production chain are shown in Table 1.

The SSDI system is composed by a pump (280 kg of cast iron) and a long drip tubing with the following characteristics: 11,000 m PE pipe ha^{-1}, 16 mm inside diameter, 18 g m^{-1}. Drip lines were placed 0.9 m apart, at a depth of 0.2 m below ground. Pressure-compensating emitters with a flow rate of 1 L h^{-1} were spaced 0.5 m apart. This drip system has durability longer than 20 years. Taking into account the functional units adopted in this study and one growing/harvesting season, this means 1.14 kg PE pipe 1000 kg^{-1} of rice at farm gate or 9.90 kg PE pipe ha^{-1}.

The flooded system is based on pumping for gravity which requires a pump (420 kg of cast iron) with lifetime of 20–30 years and a carbon steel irrigation pipe (600 m) with lifetime of 15 years. Lifetime of 20 years was adopted for both systems and the amount of irrigation pipe was corrected for this period. Recycling of the pumps and irrigation pipes was considered as end of life treatment for both systems.

2.3. System boundary

The system boundary comprised the field operation, including transportation after harvest, fertilizer production, irrigation system, electricity generation, packaging and transportation to the retailer (Fig. 1). All the stages included in the system boundary were taken into account to estimate the environmental performance of both scenarios.

2.4. Inventory analysis

Farm-specific data along with industrial production data (primary data - Table 1) were combined in order to model the rice production systems and electricity generation. Models for electric power production and transportation specifically developed for the Brazilian situation taking into account the electricity grid mix for 2012 and the GHG emission factors from GHG Protocol Brazil were adopted (Coltro et al., 2003; GHG Protocol Brasil, 2012).

The inventory quantities of consumption of energy and renewable/non-renewable resources, cultivated areas, yields and water usage for irrigation (water abstracted from surface water) were analyzed. Since two different irrigation systems are evaluated in this study, the environmental burdens of manufacturing, maintenance and disposal of both pumping systems were included in the system boundary. However, it is important to highlight that this study does not include the environmental burdens related to specific land preparation, trenches etc. of SSDI rice cropping system as well as capital goods, i.e. resources and energy usage to build and service agricultural machinery, trucks and other items.

2.4.1. Cultivation

Rice cropping begins by preparing the soil. Initially a desiccant is applied to eliminate the vegetation. Then, the soil is ploughed, revolved and inverted, followed by harrowing to correct any micro-relief imperfections. The leveling operation is carried out by employing a laser level to get proper water management of the paddy. After that, rice seeding is performed with an automatic seeder that inserts both the seeds and the NPK fertilizer into the soil at the following dosages: 90 kg ha^{-1} nitrogen, 60 kg ha^{-1} phosphorous, and 90 kg ha^{-1} potassium. When the rice is approximately 10 cm tall, crop irrigation starts.

The rice cropping system usually employed is the flooded production system – baseline case (Fig. 2a). It is based on flooded fields for a significant length of time and controlled water regime, which requires a pumping system with a high water flow demand (14,000 m^3 ha^{-1}) since this process is based on water drainage from the pumping point to all the crop area. Several days are needed to complete the irrigation due to the vast extension of the flooded area. Water is managed for approximately 90 days to keep the entire paddy rice continuously flooded. If any additional fertilizer is required, an application is made with a fertilizer spreader. Approximately 120 days after the beginning of the crop, the rice is ready to be harvested and transported to the industry. Consequently, this process leads to a great loss of water due to evaporation and infiltration into the soil.

In the SSDI paddy rice (Fig. 2b), irrigation is performed via a subsurface dripping system for approximately 90 days. If a fertilizer complement is needed, this is done by fertirrigation, which applies the fertilizer dissolved in water by the irrigation system. This fertilization is made directly to the root system of the plant, thereby increasing the fertilizer absorption capacity. After approximately 120 days, the rice is ready to be harvested and transported to the industry.

The practice of collecting rice straw is rarely used in this region. As straw is rich in potassium, straw removal would imply the need for additional fertilization in the following planting season in the same area.

Table 2 summarizes the field operations of both systems evaluated. Two different tractors are used, since dry area requires lower power and lower fuel consumption than flooded area.

Methane emissions due to anaerobic decomposition of organic material in flooded rice fields were estimated according to Equation (1), by employing IPCC models (IPCC, 2006).

$$EF_i = EF_c \times SF_w \times SF_p \times SF_o \times SF_{s,r} \tag{1}$$

Where:

EF_i = adjusted daily emission factor for a particular harvested area (kg CH_4 ha^{-1} day^{-1});
EF_c = baseline emission factor for continuously flooded fields without organic amendments;
SF_w = scaling factor to account for the differences in water regime during the cultivation period;
SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period;

Table 1
Life cycle stages and respective improvements applied to the rice production system (Primary data).[a]

Life cycle stage	Baseline system	New system
Cultivation	Flooded rice cropping system (flooded paddy fields)	Subsurface drip irrigated rice cropping system (SSDI)
Size of field (ha)	258	258
Water use (m^3 ha^{-1})	14,000	9000
Power installed (kW)	128.7	91.9
Pumping time (h day^{-1})	21	21
Pumping period (day)	90	15
Diesel consumption (L ha^{-1})	108.2	38.6
Yield (kg ha^{-1})	7500	8650
Electricity generation	Firewood used as fuel	Rice husk used as fuel
Lower heating value (MJ kg^{-1})	12.98	1.93
Silica (kg kg^{-1} rice husk)	–	0.22
Drying	Firewood furnace and temperature rate system with high grains breakage	Steam radiators and homogeneous temperature system with reduced grains breakage
Yield – whole grain (%)	60	61
Milling	Without rice recovery	Rice recovery after husk removal
Recovery rate (%)	–	60
Packaging	Polyethylene from non-renewable resource, oil	Polyethylene from renewable resource, sugar cane
Renewable resource (%)	–	57
Transportation	Conventional diesel truck fleet	More efficient diesel truck fleet
Diesel consumption (km L^{-1})	3.0	3.5
Sulfur content (mg L^{-1})	500	10

[a] Data refers to one growing/harvesting season (2012/13).

SF_o = scaling factor should vary for both type and amount of organic amendment applied;
$SF_{s,r}$ = scaling factor for soil type, rice cultivar etc., if available.

Since there are no emission factors specifically stated for Brazil, emissions were calculated based upon Tier 1 approach. A baseline emission factor (EF_c) of 1.30 kg CH_4 ha^{-1} day^{-1}, which considers no flooding for less than 180 days before rice cultivation and continuous flooding during rice cultivation without organic amendments, was adopted as the starting point.

Scaling factors were used to adjust the baseline emission factor taking into account the following rice cultivation conditions: water regime before and during the cultivation period; aeration periods and organic amendments. Specifically, flooded fields for a significant period of time and a fully controlled water regime (scaling factor for water regime during the cultivation period – $SF_W = 1$ – continuously flooded was adopted for the baseline system); regular rainfed fields whose water regime depends solely on precipitation ($SF_W = 0.28$ was adopted for the SSDI system); non-flooded pre-season longer than 180 days and rice straw incorporated longer than 30 days before cultivation (scaling factor for water regime in the pre-season before the cultivation – $SF_p = 0.68$ was adopted for both production systems) were considered (Table 3).

During the rice cultivation stage, straw is also produced, which is usually chopped and incorporated into the soil to improve its quality. However, straw can also be used for energy generation or as animal bedding. The environmental impacts had to be divided

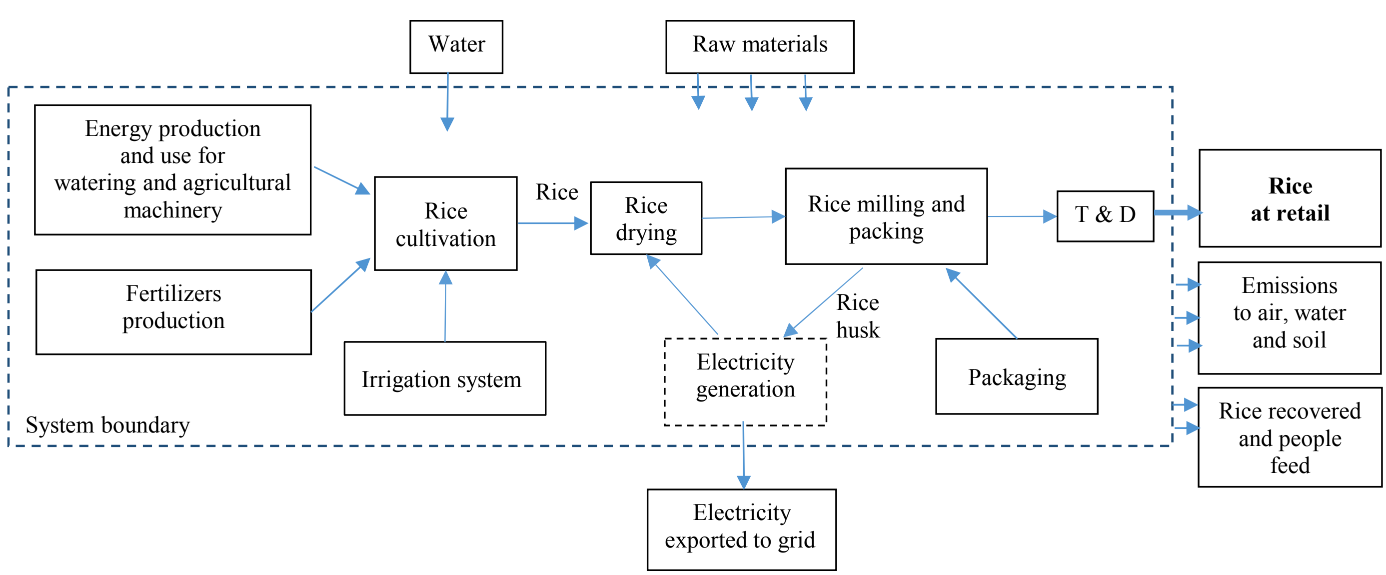

Fig. 1. System boundaries adopted in this study (T & D = transport and distribution). The dashed line indicates stages considered only in the new system.

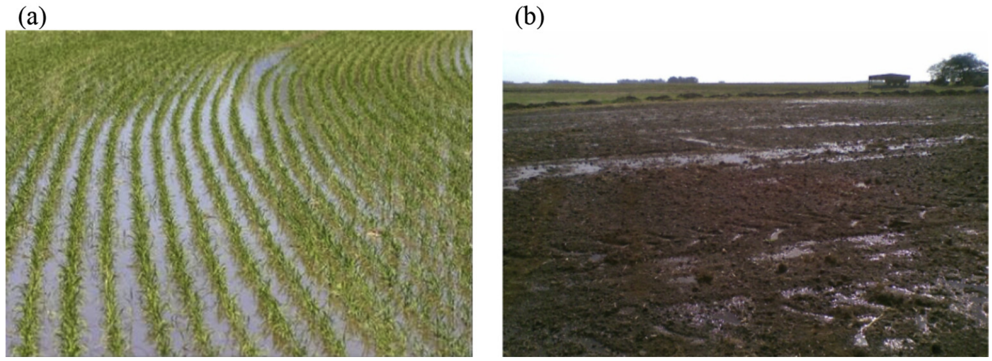

Fig. 2. Irrigation of rice cropping system moved from: (a) Flooded system – baseline case to (b) SSDI system – new production system.

Table 2
Field operations of both paddies evaluated in this study.

Machinery		Flooded system	SSDI system
Farm tractor Combine harvester		6 cylinders, 120 HP, 12 L diesel h^{-1} 6 cylinders, 260 HP, 34 L diesel h^{-1} (flooded area)	Farm tractor, 4 cylinders, 100 HP, 8 L diesel h^{-1} Combine harvester, 6 cylinders, 260 HP, 24 L diesel h^{-1} (dry area)
Field operations		Usage time (h ha^{-1})	
Weed control	Sprayer	0.3	0.08
Ploughing	Plough	2.5	2.5
Harrowing	Rotary harrow	1.0	–
Leveling	Laser level	2.5	0.5
Seeding and mineral fertilization	Automatic seeder and fertilizer applicator	1.0	0.25
2nd mineral fertilization	Fertilizer spreader	0.3	[a]
Irrigation	Water pump	See Table 1	See Table 1
Harvest	Combine harvester	0.5	0.5

[a] Fertirrigation.

between the co-products rice and straw, which was performed by system expansion for both systems evaluated.

The scaling factor for organic amendments (SF_o) applied was calculated taking into account the application rate of organic amendment, specifically rice straw (in dry weight). A ratio of paddy rice production/rice straw production of 1:0.75 was considered based on the study developed by Shafie et al. (2014). Then, 5.06 ha^{-1} of rice straw - baseline system, and 5.84 t ha^{-1} of rice straw - new system, incorporated as organic fertilizer were estimated. The conversion factor for straw incorporated a long time (>30 days) before cultivation (CFOA = 0.29) was adopted. The resulting SF_o was 1.70 for the baseline system and 1.79 for the new system (Table 3).

The resulting daily emission factors (EF_i) from the above conditions were 1.51 kg CH_4 ha^{-1} day^{-1}- baseline system and 0.44 kg CH_4 ha^{-1} day^{-1} - new system. Considering cropping cycles of 120 days on average, the estimated annual methane emission from rice cultivations was 180.77 kg CH_4 ha^{-1} y^{-1} – baseline system and 53.29 kg CH_4 ha^{-1} y^{-1} – SSDI system (Table 3).

2.4.2. Sensitivity analysis on methane emission

A sensitivity analysis was performed on both systems in order to evaluate the influence of the choices made during the modeling of the methane emission at the cultivation stage. The emission factors were modified according to the minimum and maximum values defined by IPCC and the aggregated case as well. Thus, the methane emission was estimated by taking into account three scenarios: 1) all minimum values, 2) all maximum values and 3) aggregated case scaling factors.

2.4.3. Production and application of fertilizers

The environmental aspects relating to the production of NPK fertilizers (175 kg ha^{-1} as urea, 100 kg ha^{-1} as monoammonium phosphate - MAP (60% phosphorous and 12% nitrogen) and 150 kg ha^{-1} as potassium chloride (60% potassium) were taken from recognized database available in GaBi 6 Product Sustainability software program and included in the boundary. Specifically, urea (technology mix, nitrogen content 46%), MAP (technology mix, phosphorus compound contents 52% and nitrogen contents 11%) and potassium chloride (technology mix, potassium compound contents 60%). Emissions of nitrogen and phosphate from production and application of fertilizers were included within the system boundary according to the following descriptions. Nitrate emissions were estimated according to Brentrup et al. (2000). Emission of nitrous oxide (N_2O) to air was estimated as 1.25% of N-based fertilizer following the IPCC guidelines (IPCC, 2006). Emissions of nitrogen oxides (NO_x) were assumed to be 2% and ammonia (NH_3) emissions were assumed to be 8%. Nitrate leached to water was

Table 3
Methane field emissions estimated for both systems evaluated.

Parameter	Flooded system	SSDI system
SF_w	1.0	0.28
SF_p	0.68	0.68
SF_o	1.70	1.79
ROA_i	5.06	5.84
$CFOA_i$	0.29	0.29
EF_i (kg CH_4 ha^{-1} day^{-1})	1.51	0.44
EF_y (kg CH_4 ha^{-1} yr^{-1})	180.77	53.29

estimated as 30% of N-based fertilizer, while phosphate was assumed to be 1% of the P-based fertilizer (Erickson et al., 2001; Smil, 2000).

2.4.4. Electric energy generation

Rice husk is generally used as bedding material and as an energy source. In the modern rice milling industry, rice husk is being increasingly used as a fuel source for grain drying and electricity generation.

Rice husk was used as fuel to replace firewood at the Alegrete Electric Power Plant Ltd. - GEEA project. In this project, 220 kg of rice husk produced per 1000 kg of paddy rice was used to generate 529.2 MJ, which is the monthly power consumption of a medium-low class household. Rice husk low heating value of 12.7 MJ/kg was adopted (Brazilian Energy Balance, 2014). Following Chungsangunsit et al. (2009) equations, the overall conversion system efficiency of the plant was estimated as 19%, according to data from the power plant supplying energy to the rice production systems evaluated.

2.4.5. Drying

At this stage, the moisture content of grains was reduced from 22%, still with husk, to values of 10.5% to prevent fermentation and pest propagation (worms, moths, and caterpillars). Conventional processes use dryers with furnaces fed by rice husk or firewood to generate hot gases, which gradually remove the humidity from rice grains.

During the rice drying stage, part of the cereal may be broken due to fluctuating temperatures to which rice is exposed, oscillation in the volume of air injected in the machine as well as due to mechanical reasons, such as recirculation inside the drier.

In the traditional drying system, from a paddy rice of 68% grains, using very efficient and controlled equipment, it is possible to reach a maximum of 60% of long grains. By improving the traditional technology to a new model of drying system by replacing the traditional furnace to steam from a thermal plant, by developing precise control and distribution of hot air as well as online management of steam pressure and steam flow, constant supervision of air input, colder operating temperature and considerable reduction of mechanical recirculation, the efficiency of the process is significantly increased, considering that the percentage of long grains rises to 61% and sometimes 62% out of 68%, whereas the percentage of broken grains drops from 8% to 7% and sometimes to 6%.

Regarding drying efficiency, it is important to highlight that paddy rice is made up of 22% of husk, from 8 to 10% of bran and approximately 68% of milled grains (considering both long and broken grains). From an overall perspective, in order to be rated as high quality rice, there must be a minimum of 60% of long grains and 8% of broken grains right after drying or inside the silos.

At the drying stage, a low heating value of 12.98 MJ kg^{-1} and efficiency of 63% was considered for firewood boiler (Brazilian Energy Balance, 2014; EPA, 2003).

An average annual consumption of 14.6 kg of rice per capita was adopted in this study (IBGE, 2011).

2.4.6. Milling

Milling is an important stage in post-production of rice. The purpose of this stage is to remove husk and bran layers, and produce edible, impurity-free white rice. Rice husk is generated in the beginning of rice milling when paddy rice is husked. The rice recovery of the new rice production system works by weight difference between the rice husk and the grains. All rice hull produced at Pilecco Nobre was sent to GEEA to be used as raw material both for electricity generation and silica extraction. However, a fraction of husked rice as well as paddy rice was lost during the husking process, as it was sent together with the rice husk itself to the electric power plant.

2.4.7. Packaging

The usual rice packaging is a polyethylene bag with 5-kg net weight capacity. This packaging was changed from polyethylene from oil (non-renewable resource) to polyethylene from sugar cane ethanol (renewable resource). The polyethylene from renewable resource has the same properties, performance and versatility of applications as the polyethylene from oil, which makes its use easy. For the same reason it is recyclable in the same recycling chain of conventional polyethylene.

The amount of non-renewable resources - oil, oil derivatives, gas, and coal (1.59 kg kg^{-1} polyethylene) and CO_2 emission (2.0 kg kg^{-1} polyethylene) of the oil-based plastic was obtained from PlasticsEurope's Eco-profiles (PlasticsEurope, 2014).

According to a producer of polyethylene from renewable resource (Novaes, 2010), 1 kg of polyethylene from renewable resource captures and fixes 2.0–2.5 kg CO_2 as a balance among photosynthesis, transport and chemical process emissions. However, this CO_2 fixation was not taken into account due to lack of reliable data in the scientific literature.

Therefore, the quantity of renewable resource of the new packaging refers to the amount of fossil polyethylene replaced. It does not consider the amount of sugar cane used to produce the plastic. The mitigation of CO_2 emission refers only to the CO_2 related to the quantity of oil-based polyethylene replaced.

2.4.8. Transportation

Rice used to be distributed via truck fleets running on conventional diesel oil, which emitted 500 mg of sulfur per liter and had an average fuel consumption of 0.33 L diesel km^{-1}. In order to mitigate the environmental impact of this life cycle stage, the entire fleet of seven trucks was replaced by new trucks that run on diesel S10, which emits 10 mg of sulfur per liter, besides an average fuel consumption of 0.29 L diesel km^{-1}.

2.4.9. Allocation

At the cultivation stage, the environmental burdens due to the manufacturing, maintenance and disposal of the irrigation systems were estimated taking into account the following parameters: average lifetime of 20 years for both irrigation systems, yield of 7500 kg ha^{-1} (flooded system) and 8650 kg ha^{-1} (SSDI system) and area of rice production (258 ha). Averages of 38,700 t (flooded system) and 44,634 t (SSDI system) of rice produced during the lifetime of the irrigation systems were estimated, which gave allocation factors of 2.58 10^{-8} (flooded system) and 2.24 10^{-8} (SSDI system) assigned to the systems evaluated in this study.

Besides, rice cultivation produces two co-products, rice and straw. The latter can be used for energy generation, animal bedding or as organic amendment. Since the systems evaluated in this study use straw as organic fertilizer added to the soil, no allocation was applied to rice straw.

The milling stage is a multifunctional process which produces four co-products: white milled rice, broken rice, rice bran and rice husk. In this case, allocation criteria should be adopted in order to share environmental burdens among the chain subsystems and estimate environmental burdens that are assigned only to rice. An allocation based on economic value of white milled rice and co-products was adopted, as several authors have done on LCA studies applied to rice production (Blengini and Busto, 2009; Kasmaprapruet et al., 2009; Brodt et al., 2014). Therefore, approximately 93% of the environmental burdens was attributed to white milled rice as shown in Table 4. At the new system, husk from the milling stage is used as fuel to generate vapor consumed at the

Table 4
Economic allocation adopted for rice and co-products at milling stage.

Product	Market value (US$/t of product)	Percentage (by weight)		Market value (US$/t of rice)		Allocation factor	
		BS	NS	BS	NS	BS	NS
White milled rice	1006.87	60.0	60.1	604.15	605.01	93.41%	93.44%
Broken rice	254.10	8.0	8.0	20.33	20.33	3.14%	3.14%
Rice bran	183.05	10.0	9.9	18.30	18.14	2.83%	2.80%
Rice husk	18.30	22.0	22.0	4.03	4.03	0.62%	0.62%
		100.0	100.0	646.80	647.51	100%	100%

BS = Baseline system; NS = New system.

Table 5
Economic allocation adopted for co-products at power generation stage.

Product	Market value (US$)	Co-product/t of rice husk	Market value (US$/t of husk)	Allocation factor
Silica	0.20/kg	218.18 kg	43.64	57%
Electricity	0.014/MJ	2405.45 MJ	33.41	43%
			77.05	

drying stage. However, no allocation was applied to husk since this co-product has low economic value (0.6%) and it is usually considered as waste.

The power generation stage of the new system evaluated in this study also generates two co-products: silica and energy (part consumed by the system and part exported to the grid). Both co-products from the power generation stage have economic value and they are exported to other systems. Therefore the environmental impacts were split between the co-products based on economic allocation, as shown in Table 5. The allocation factors adopted in the several stages of this study are summarized in Fig. 3.

2.5. Impact assessment

The environmental impact categories adopted in this study are those considered most relevant for the Brazilian situation. Climate changes (global warming potential for a 100-year perspective - GWP_{100}, excluding biogenic carbon), eutrophication potential (EU) and acidification potential (AP) were estimated according to the CML 2001–April 2013 method (Guinée, 2002), since this method is globally oriented and more appropriate to Brazilian situation. The primary energy demand (PED) from renewable and non-renewable resources (net calorific value) was calculated using the GaBi 6 Product Sustainability software program, which takes into account direct and indirect fuel consumption (machinery and fertilizers). Land use and rice loss were also considered. Data storage and modeling were performed by means of the GaBi 6 Product Sustainability software program (PE, 1992–2015).

3. Results

The improvements made to rice cultivation, power generation, milling, packaging and transportation are described below, as well as the mitigation of environmental impacts due to changes made along the chain.

3.1. Cultivation

Replacing the flooded system for the SSDI system (Fig. 2b) enables the plant's root system to absorb water directly, resulting in a 42% reduction in water demand per hectare (or 50% per ton of rice at farm gate) and a 90% reduction in electric power consumption (Table 6). The SSDI system also prevents water loss by evaporation and shifting since it is based on a system of channels that direct the water flow always to the same place. Besides, the SSDI system allows all fertilizers and pesticides to be applied with minimal loss as reported in the literature (Ayars et al., 2015; Devkota et al., 2015).

Active ingredients for weed control are the same in both systems evaluated, but weed control operations are longer in flooded system since application of pesticides in flooded area is more difficult.

The yield of the SSDI system was 15% higher than the baseline system even though the same amount of fertilizers was applied to both. This is probably due to better control of water supply to avoid the delay in flooding the entire irrigated area, which might affect plant development in some parts of the rice paddy. The development of the paddy rice in the new system is shown in Fig. 4.

A reduction of 29% in eutrophication and 70% in the acidification impact categories was estimated as a consequence of the higher yield of the SSDI system. This means a reduction of 7.50 kg of NPK 1000 kg^{-1} rice at farm gate. However, a more pronounced reduction in use of fertilizers is expected with the SSDI system due to the decrease in iron toxicity problems.

The SSDI system has 66% lower GWP_{100} (232.56 kg CO_2-eq 1,000 kg^{-1} rice at farm gate) than flooded paddy fields (690.07 kg CO_2-eq 1,000 kg^{-1} rice at farm gate) mainly because 70% emissions of methane from anaerobic decomposition of organic matter are prevented (Fig. 5). Besides, the SSDI system displayed a 69% drop in fuel combustion owing to lower diesel consumption by the agricultural machinery working on dry soil instead of flooded field, and 90% lower electricity consumption due to lower-powered water pump and fewer days of water pumping. Regarding irrigation systems, 4.5% of the GHG emissions of the baseline system is due to production and maintenance of the irrigation system but its contribution to the SSDI system is only 1.3%.

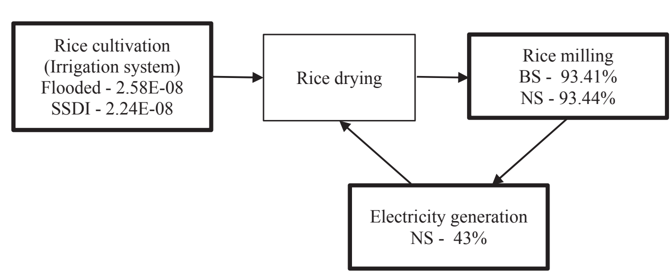

Fig. 3. Allocation factors adopted in this study. (BS = Baseline system; NS = New system).

Table 6
Mitigation of environmental aspects at cultivation stage (Baseline system vs. New system).[a]

Aspects/Impacts	Unit	FU = 1 ha		FU = 1000 kg at farm gate	
		Value	%	Value	%
Primary energy demand	MJ	15,773.11	56	2318.67	62
Electric power consumption	MJ	5212.60	88	707.50	90
Non-renewable energy	MJ	6752.71	39	1089.12	47
Water use	m^3	6751.16	42	1066.46	50
Non-renewable energy resources	kg	176.98	40	28.25	48
Renewable fuels	kg	72.28	88	9.81	90
Fertilizers	kg	0	0	7.47	13
Diesel	kg	57.08	64	8.17	69
Land use	m^2.yr	0	0	177.26	13
Yield	kg ha^{-1}	(1150.00)	(15)	(1150.00)	(15)
GWP_{100}	kg CO_2-eq	3163.85	61	457.51	66
Eutrophication (EP)	kg PO_4^{3-}-eq	1.50	18	0.32	29
Acidification (AP)	kg SO_2-eq	6.31	66	0.90	71
Abiotic depletion (ADP fossil)	MJ	6157.13	38	1000.30	46

FU = Functional unit.
[a] (Indicates increase).

Fig. 4. Sequence of paddy rice development in the new production system.

Fig. 6 shows the results of the sensitivity analysis on methane emission of both systems under study. As can be seen, there is a large influence of the IPCC emission factors on the results, ranging from −44% (minimum values) to +76% (maximum values). Both systems are approximately 40% far from the minimum values and approximately 70% far from the maximum values, but the baseline system is closer to the aggregated case than the new system.

However, the lower methane emissions from the baseline system to the new system, taking into account the four scenarios (disaggregated, aggregated, minimum and maximum values), are 71%, 64%, 72% and 69%, respectively, i.e., approximately 70% in all cases. Thus, the conclusion is that the sensitivity of methane emissions from rice cultivation in both systems is not critically sensitive to data modeling. The data is therefore deemed acceptable.

The installed pumping power of the SSDI system is lower than that of the flooded system, since the water flow demand of the former is lower (9000 m^3 ha^{-1}) than the baseline case, resulting in a large drop in energy consumption, i.e., 2318.67 MJ 1000 kg^{-1} rice at farm gate or 90%, as shown in Fig. 7.

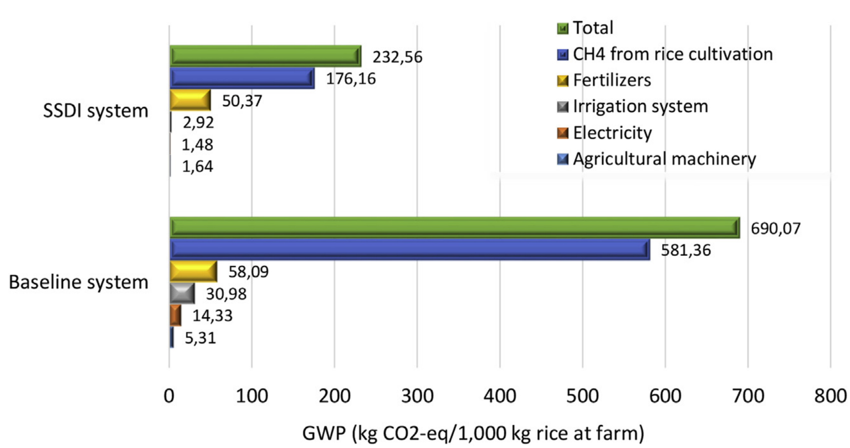

Fig. 5. Contribution of the inputs to the GWP_{100} of the rice cultivation stage (FU = 1000 kg rice at farm).

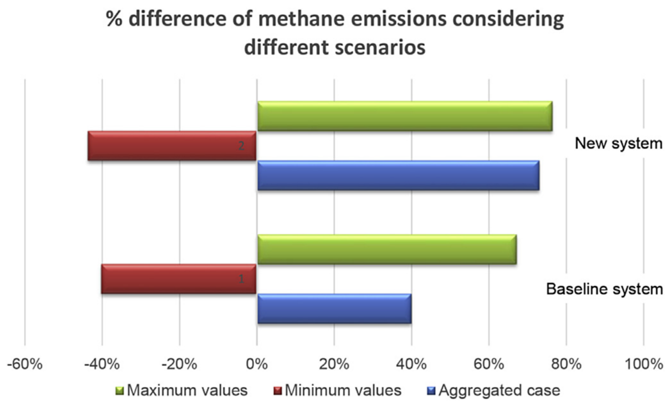

Fig. 6. Results of the sensitivity analysis on methane emission from rice cultivation.

While consumption of electric power for irrigation and production of fertilizers are the main contributors to the primary energy demand of the baseline system, production of fertilizers is by far the top contributor to the primary energy demand of the SSDI system (Fig. 7). Irrigation system accounts for 8.8% of the primary energy demand of the baseline system and 6.5% of the SSDI system. In both systems, PED of the irrigation system is half of the PED of the agricultural machineries (which are based on diesel combustion).

A significant reduction in diesel consumption (8.14 kg 1000 kg^{-1} rice at farm gate or 69%) was observed in the SSDI system due to the shorter usage time of agricultural machinery for planting, maintenance and harvesting since the soil is not flooded.

3.2. Electricity generation

Deducting the energy consumption of the power plant and the steam sent to the rice drying system, an amount of 497.87 MJ 1000 kg^{-1} packed rice was produced and exported to the power grid. This represents the monthly electricity consumption of 1 medium-low class households.

The bulk density of rice husk is 100–150 kg m^{-3} and it contains 16–22% ash that is high in silica. Therefore, 48 kg of silica was obtained from 220 kg of rice husk which replaces 96 kg of cement in conventional concrete mixtures or 129.09 kg 1000 kg^{-1} packed rice.

3.3. Drying

If rice drying is not well controlled, the grains can be degraded by breakage due to formation of temperature gradient. Rice grains may break also because of the high recirculation required by conventional dryers to get high productivity. Broken grains are not used as quality rice.

For these reasons, in the second half of 2012 a drying system fed by steam from the GEEA thermal power plant was installed. Besides eliminating firewood, this equipment has a differentiated system of drying racks that provide more homogeneous distribution of hot air, thus preventing grains from breaking due to temperature gradient, as shown in Fig. 8. Since this drying system is more efficient than the conventional one, it reduces recirculation of grains inside the equipment, which decreases breakage caused by moving.

The benefit from this improvement is the use of 256.00 MJ of renewable energy from waste, avoiding the use of 176.81 kg of firewood 1000 kg^{-1} packed rice. Moreover, a better yield of whole rice grains (16.67 kg 1000 kg^{-1} packed rice) was achieved which is equivalent to the amount of rice 1.14 Brazilians consume per year. By drying rice more efficiently, the amount of broken grains sold at a low price drops and the company can process and commercialize more rice for human feeding.

3.4. Milling

The implementation of the rice recovery equipment in the milling stage allowed recovering 2.36 kg rice 1000 kg^{-1} packed rice that used to be burnt with the rice husk at the electric power plant. 1.42 kg of recovered rice is suitable for human consumption and the remaining 40% is used as animal feed. Therefore, this improvement increased the yield of the productive system.

3.5. Packaging

Taking into account the functional unit of 1000 kg packed rice, the benefits of this improvement are the usage of 2.07 kg of renewable resources, reduction of 3.75 kg of non-renewable resources (oil) and 167.26 MJ non-renewable energy consumption, as well as a decrease of 4.92 kg CO_2-eq. The latter is due to CO_2 emissions associated to oil extraction and polyethylene production, while CO_2 fixation by sugar cane was not taken into account due to lack of reliable data in the scientific literature.

3.6. Transport

The changes made in the transportation and distribution stage resulted in a reduction of 1.68 kg in consumption of non-renewable resources (oil) 1000 kg^{-1} packed rice, 71.33 MJ of non-renewable energy, as well as lower GWP (5.48 kg CO_2-eq) and acidification

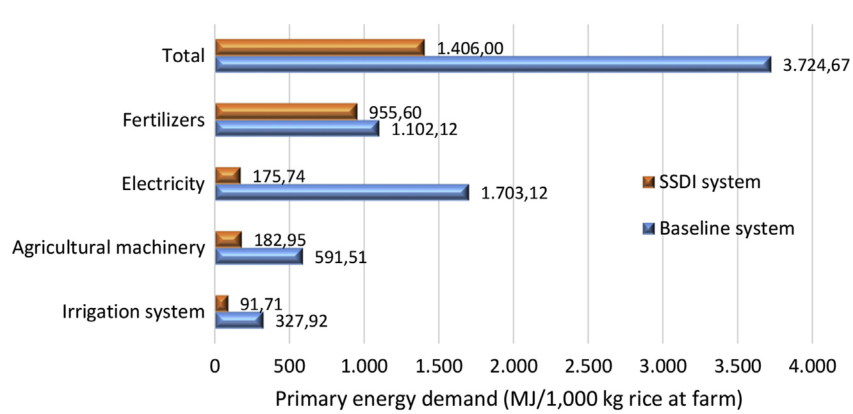

Fig. 7. Contribution of the inputs to the primary energy demand of the systems (FU = 1000 kg rice at farm).

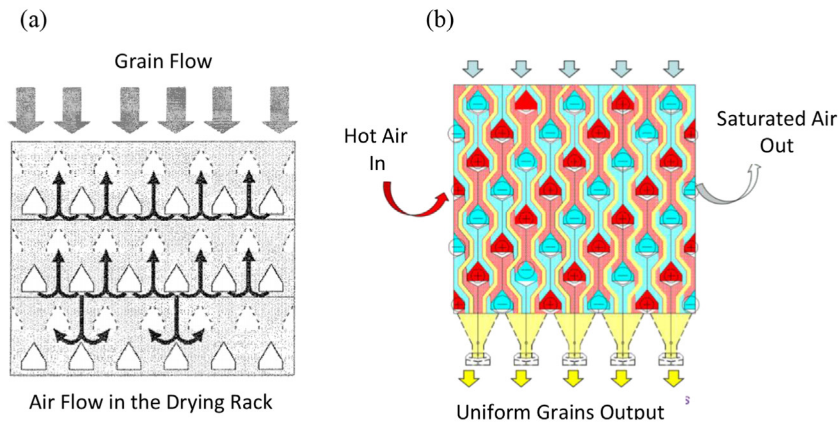

Fig. 8. Drying systems: (a) conventional drying rack, (b) new system of drying rack.

potential (0.08 kg SO_2-eq) lower than the previous fleet of trucks. These results were due to higher efficiency of the engine of the new trucks and the use of diesel oil with lower sulfur contents.

4. Discussion

Table 7 shows a comparison between the inputs and yield of this study and those presented in the LCA of paddy rice production in Northern Iran developed by Mohammadi et al. (2015). As can be seen, the use of diesel oil in the present study is much lower than the reference, while the use of water for irrigation is similar. The water used by the new system is close to the spring fields and the traditional system is similar to the summer fields. Consumption of electricity and fertilizers stated in the present study are lower than the consumption mentioned by Mohammadi et al. (2015). Nevertheless, the yield of the present study is much higher. The yield of the present study ranks among the highest values recorded for the global distribution of rice yield, which are mainly in the range of 2–4 t ha^{-1}, 4.6 t ha^{-1} on average (Nemecek et al., 2012).

Table 8 shows the results of some LCA studies applied to rice production in different countries (Thailand, Iran, Italy and USA) and corrected to the same functional unit for comparison purposes. As can be seen, the GWP_{100} of the baseline production system evaluated in this case study is similar to the results obtained for the baseline scenario of the study developed in the North of Italy and in consolidated farms evaluated at Gilan Province, Iran, both of which are based on flooded systems with incorporation of straw into the soil. However, the GWP_{100} of the new production system analyzed in this case study showed lower values than the other studies, particularly due to the SSDI rice cropping system in a rainfed field where the water level may be as high as 50 cm during the cropping season for a significant length of time, with consequent decrease of methane emissions from anaerobic decomposition of organic material.

Regarding eutrophication and acidification potential, the results obtained in this study are close to the results of the study developed in Gilan Province, Iran, but much lower than the results stated in other studies.

The combination of the improvements clearly produced substantial mitigation of the environmental impacts of rice production, particularly less water usage, primary energy demand, abiotic depletion and consumption of renewable resources as well as GWP. Table 9 summarizes the relative mitigation of the environmental impacts considered in this study, taking into account all the improvements made to the rice production system. Fig. 9 shows the contribution of each life cycle stage to the improvement of the system.

The life cycle stage that contributed the most to reduce the environmental impact of the rice production system was rice cultivation (mitigation of 12 environmental aspects/impacts, besides higher yield); the drying stage contributed mainly to reduce rice loss, use of renewable resources and to decrease the primary energy demand. Electricity generation accounted for higher use of renewable resources besides silica production both from rice husk. The greatest contribution to decrease the environmental impact of packaging was to reduce abiotic depletion, use of non-renewable energy resources and non-renewable energy. Transport accounted for lower diesel oil consumption and consequent lower abiotic depletion, lower use of non-renewable energy resources and non-renewable energy, besides less acidification and water use. Milling contributed to reduce rice loss.

The key opportunity in terms of environmental benefits is the decrease in water consumption (approximately 2800 m^3 1000 kg^{-1} of packed rice) which is approximately twice the magnitude of the water footprint of rice production in Brazil (1521 m^3 t^{-1}) as estimated by Chapagain and Hoekstra (2011). According to these authors, the total water use (water footprint plus percolation and residual soil moisture) of rice production in Brazil is 2797 m^3 t^{-1}, which is close to the amount of water used by the baseline system evaluated in the present study (2151.07 m^3 t^{-1} rice at farm gate).

Moreover, there is a correlation between the amount of water used per hectare and soil acidification. This means that the more

Table 7
Farm inputs and yield used in the present study compared to literature data (reference unit = 1 ha).

Production system	Reference	Electricity (kWh)	Water (m^3)	Fertilizers (kg)	Diesel (L)	Yield (kg)
Baseline system[a]	Present study	1644	14,000	425	108.2	7500
New system[b]		196	9000	425	38.6	8650
Spring fields	Mohammadi et al. (2015)	1956	9320	287	301	5766
Summer fields		2032	13,823	278	491	4516

[a] Flooded paddy fields.
[b] SSDI paddy fields.

Table 8
Environmental impacts of rice production in different countries (FU = 1000 kg rice at farm gate).

Production system	GWP_{100} (kg CO_2-eq)	EP (kg PO_4^{3-}-eq)	AP (kg SO_2-eq)
This study (Brazil)[a]			
Baseline system	689.93	1.11	1.27
New system	232.56	0.79	0.37
Northeastern Thailand[b,c]			
Wet-season irrigated rice	4870	80	40
Dry-season irrigated rice	5550	100	50
North of Iran[b,d]			
Spring rice paddy production	1263	21.3	9.9
Summer rice paddy production	1911	30.5	13.8
Guilan Province, Iran[e]			
Consolidated farms	763.0	0.52	3.46
Traditional farms	1312	0.85	6.04
North of Italy[f]			
Baseline scenario	669.9	8.54	13.9
Alternative scenario	416.2	4.83	6.1
California, USA[b,g]			
Measured field emissions	1010	n.a.	n.a.
IPCC Tier 1 emissions	1090	n.a.	n.a.

n.a. = not available.
[a] Baseline system = Flooded paddy fields; New system = SSDI paddy fields.
[b] The results of these references were corrected to the functional unit of this study, i.e. 1000 kg rice at farm gate.
[c] Thanawong et al., 2014.
[d] Mohammadi et al., 2015.
[e] Khoshnevisan et al., 2014.
[f] Fusi et al., 2014.
[g] Brodt et al., 2014.

water used per hectare, the greater the probability of problems with iron toxicity in the following harvest. Iron toxicity occurs more frequently in flooded rice grown on acid soils.

In acid soils, where Fe is most available, Fe^{2+} can become toxic to plants. Reducing conditions are developed on these soils due to flooding which lead to reduction of Fe^{3+} to Fe^{2+}. As a consequence, Fe^{2+} concentration and incorporation by the plant is increased. The metal toxicity in the flooded paddy rice can be related to nutritional imbalance, i.e., excess Fe in the growth medium may inhibit uptake, transport and utilization of many other nutrients by the plant and cause nutritional deficiency. The most relevant nutrient deficiencies observed in flooded rice in Brazil are P, K and Zn (Fageria et al., 1990).

Reducing conditions in the soil are much lower in the SSDI system than in the flooded system since flooding is avoided. This problem is corrected by applying lime, but there is no technical data to quantify the reduction of lime use until the date of publication of this study. The confirmation of this reduction will be available only in 2016 when more crops will be evaluated.

This is relevant considering the water scarcity we are facing nowadays because of climate changes. According to the last IPCC (2014), the climatic changes already observed and the forecasts of climate changes in South America will compromise water availability in this region, and direct impacts should take place in the water supply to households and industries as well as in sectors that strongly depend on water, such as hydroelectricity production and agriculture.

According to the study of Nemecek et al. (2012), which appraised the variability in the global warming potential of 27 crops, the highest globally averaged GWP per hectare was rice, ranging from 9500 to 11,500 kg CO_2-eq ha^{-1}. The key causes of this high impact relate to the large consumption of irrigation water and emissions of methane, which contribute with approximately two thirds to the GWP. In the present study, the GWP per hectare was 5174.48 kg CO_2-eq ha^{-1} – baseline production system and 2011.68 kg CO_2-eq ha^{-1} – new production system. These low values are probably associated to high yields of the systems under analysis, which are 63% (baseline) and 88% (new system) higher than average yield of rice crops evaluated by Nemecek et al. (2012). Additionally, in the present study electricity was used for irrigation of the systems instead of combustion of fossil fuels, which contributes to a lower GWP of crop production, since CO_2 emissions of electricity in Brazil are low due to the high percentage of hydropower generation of the Brazilian electric power grid (Coltro et al., 2003). This may also be the reason why field emissions of methane account for approximately 85% of the GWP of the baseline production system (8% - production and application of fertilizers, 4.5% irrigation system and 2% electricity). Field emissions of methane accounted for approximately 76% to the GWP of the new production system (22% - production and application of fertilizers, 1.3% irrigation system and 0.6% electricity).

Another important benefit derived from the improvements made to the rice production chain was an increase of 15% in yield, which means less usage of land for rice cultivation, fewer inputs (fertilizers, pesticides etc.) and associated emissions, besides feeding more people without increasing the cultivated area.

Table 9
Mitigation of environmental impacts and improvements of the rice production system under analysis: baseline production system vs. new production system (FU = 1000 kg packed rice at retail).

Parameter	Unit	Quantity			%
		Baseline system	New system	Improvement	
Yield	kg ha^{-1}	7500.00	8652.36	1152.36	15
Silica	kg	0.00	129.09	129.09	–
Renewable resources	kg	176.81	256.00	79.19	45
Rice recovery	kg	0.00	18.08	18.08	–
Electric energy exported to the grid	MJ	0.00	497.87	497.87	–
				Mitigation	
Primary energy demand	MJ	10,477.89	4158.97	−6318.92	60
Electric energy consumption	MJ	2047.19	207.51	−1839.68	90
Non-renewable energy	MJ	6804.50	3692.34	−3112.16	46
Water use	m^3	5582.56	2766.78	−2815.78	50
Non-renewable energy resources	kg	170.10	90.32	−79.78	47
Land use	m^2.yr	3704.00	3153.86	−550.14	15
GWP (100 yr)	kg CO_2-eq	1843.54	629.48	−1214.06	66
Eutrophication (EP)	kg PO_4^{3-}-eq	2.96	2.06	−0.90	30
Acidification (AP)	kg SO_2-eq	3.64	1.22	−2.42	66
Abiotic depletion (ADP fossil)	MJ	6390.92	3525.44	−2865.48	45

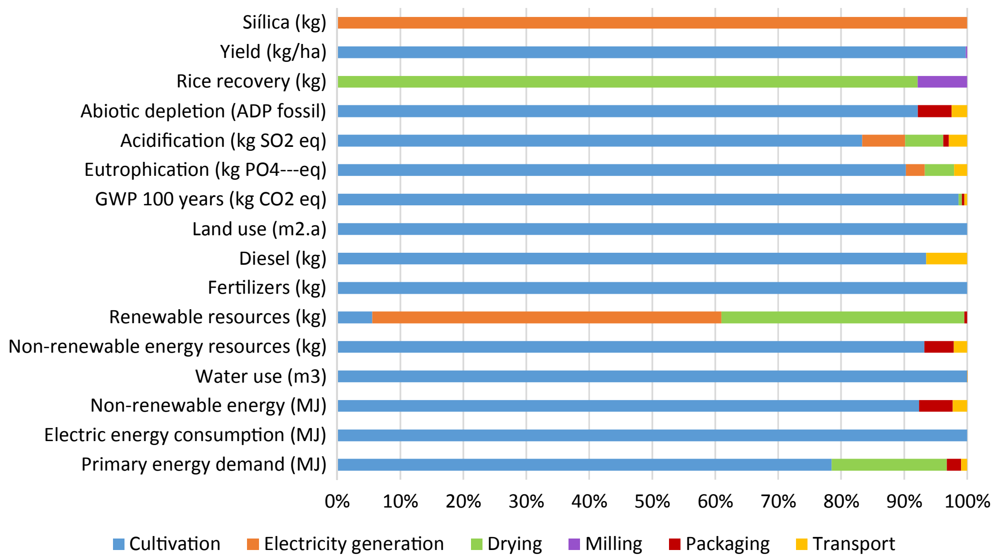

Fig. 9. Contribution of each life cycle stage to the environmental performance of the product.

The SSDI system adopted in the cultivation stage accounted for the largest part of the environmental impact mitigation, i.e. primary energy demand, electric power consumption, consumption of water and non-renewable resources, land use, yield, GWP, eutrophication and acidification.

However, the other improvements made along the rice production chain also contributed to mitigate the environmental impact of the product, such as: 1) the electricity generation stage contributed to reduce power consumption from the grid and to produce silica, which replaces cement in conventional concrete mixtures, besides exportation of electricity to the grid; 2) the new drying system contributed to reduce consumption of renewable resources (firewood) and primary energy demand; it was also responsible for preventing most of the rice loss and for increasing the number of people fed; 3) the equipment for rice recovery after husking at the milling stage was responsible for reducing rice loss and, as a consequence, increasing the number of people fed; 4) the change made to the packaging material contributed to reduce the use of non-renewable resources and non-renewable energy as well as the use of renewable resources, and 5) the alterations made in the transportation stage contributed to reduce the use of non-renewable resources and non-renewable energy owing to lower consumption of diesel oil.

In order to demonstrate the importance of the results obtained, an estimation was made of the mitigation in the whole area assessed in this study (258 ha), which represents 0.01% of the rice cultivation in Brazil or 0.02% in Rio Grande do Sul. The environmental benefits regarding water use were approximately 1.74 billion liters of water saved, which is equivalent to the monthly consumption of 87,000 households. It was estimated that the reduction in consumption of electric power was approximately 375,000 kWh - corresponding to the monthly consumption of 2500 households. As to land use, rice farm uses 40 ha less nowadays.

5. Limitations

When applying LCA to study a product or service some assumptions must be made and limits established, otherwise the study never ends. Definition of the system boundary is especially difficult when the subject is food production (fruits, cereals, livestock etc.), since production stage is embedded in the environment. Therefore, due to time limitations some life cycle stages were excluded from boundary system of this study, which are: preparation of the area for SSDI system (specific land preparation, trenches etc.), manufacturing of capital goods (machinery, tractors etc.) used in the cultivation stage, production of seeds and pesticides production.

Flooded system is a traditional rice cultivation adopted by the farm evaluated in this study (>20 years) and inclusion of area preparation only for SSDI system could unbalance the systems. Regarding other exclusions cited previously, study developed by Blengini and Busto (2009) showed contribution of capital goods to the impacts of white milled rice produced in Italy ranges from 0.2% (photochemical ozone creation potential) to 6.0% (water use total); while seeds production accounts for approximately 3.0% to all impact categories evaluated and pesticides ranges from 0.1% (photochemical ozone creation potential and eutrophication potential) to 2.1% (non-renewable energy requirement). Therefore, the stages evaluated in this study covers at least 94% of the environmental impacts of the systems.

6. Conclusions

This work supplied results on the environmental performance of two distinct rice production chains. Largely reduced water consumption (approx. 2800 m^3 t^{-1} packed rice at retail) was observed in the rice cultivation owing to the replacement of the flooded rice cropping system for the SSDI rice cropping system, besides other benefits like reduced consumption of electric power (approx. 2000 MJ t^{-1} packed rice at retail) and fewer GHG emissions (approx. 1200 kg CO_2-eq t^{-1} packed rice at retail).

The entire rice production chain was improved, from farm to transportation and distribution to retail stores. The results indicated that changing irrigation from the flooded system to the SSDI system accounted for most of the savings, i.e. 50% less water consumption, 90% less electric power consumption, 30% less eutrophication, 66% less acidification, 66% lower GWP, besides 15% higher yield. The power plant based on rice husk combustion accounted for 498 MJ electric power exported to the grid and 129 kg silica produced from rice husk. The drying stage consumed 254 MJ renewable energy from waste, which meant saving 177 kg of firewood and recovering 16 kg of rice.

The 15% increase in yield was mostly a result of the new rice cultivation system and of GHG savings mainly due to avoided field methane emissions and reduced emissions derived from electricity used to pump irrigation water. It must also be noted that indirect land use changes (ILUC) were not considered in this study, which could increase GHG savings due to changes in land use somewhere else.

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