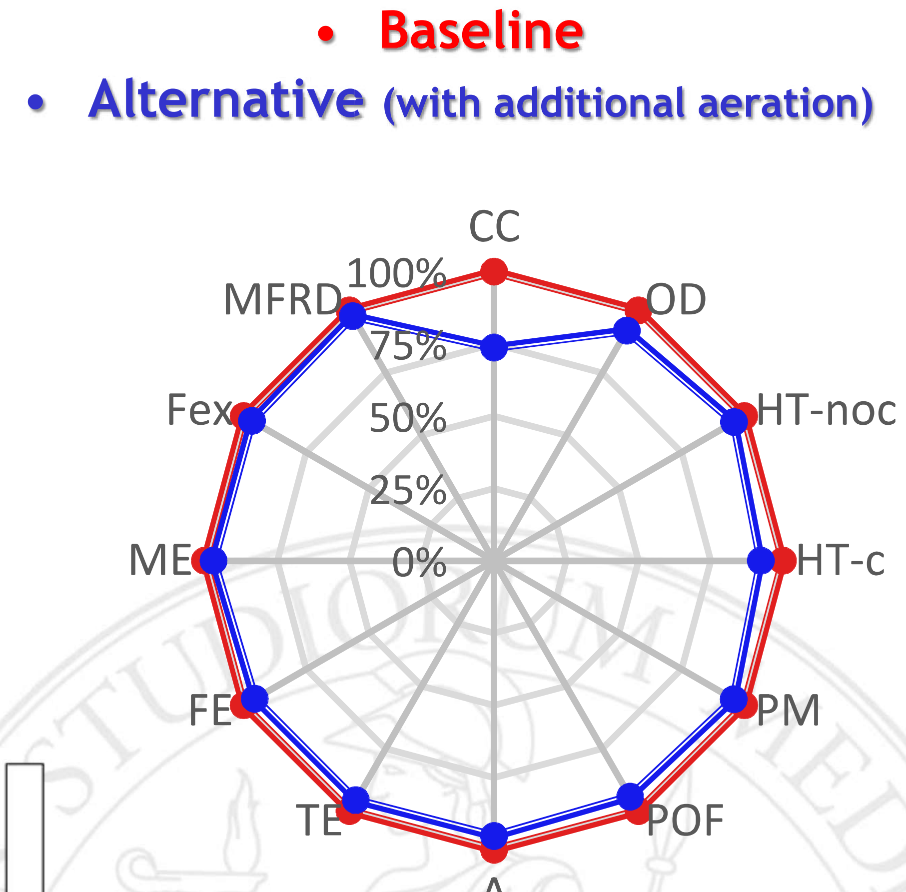
Graphical Abstract

Research questions

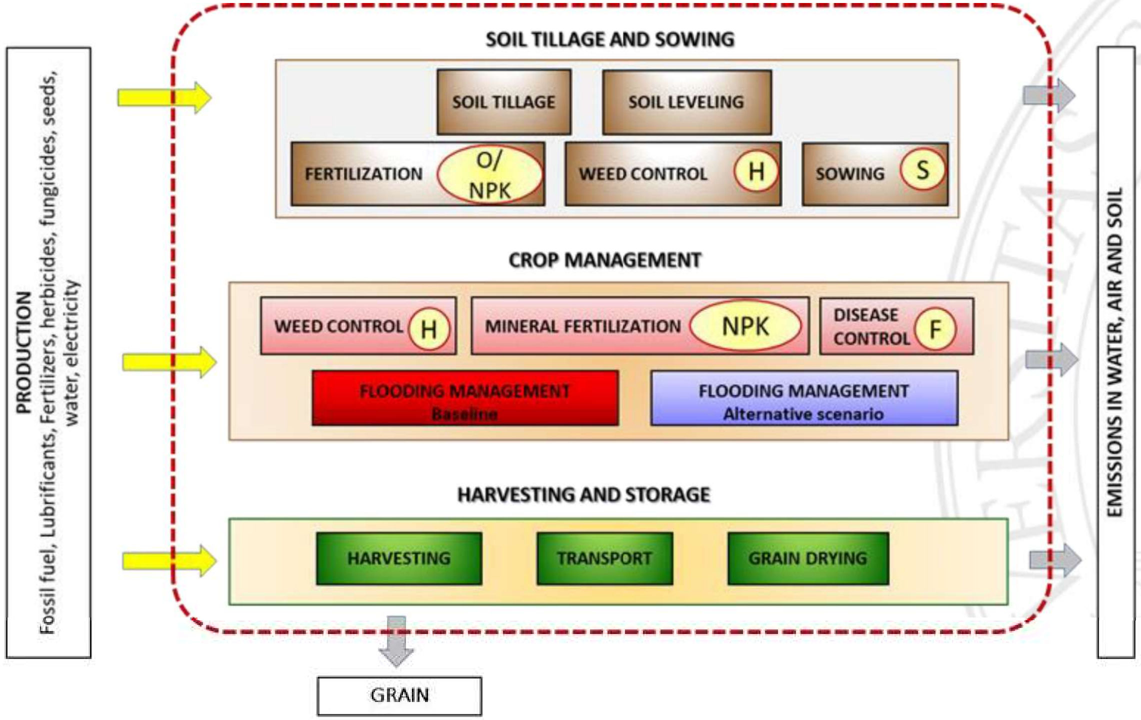
1) Can the introduction of an additional aeration period reduce the impact of paddy rice cultivation?
2) How is affected the content of heavy metal (arsenic and cadmium) by the additional aeration?

Methods

field trials + Life Cycle Assessment



Climate change (CC), ozone depletion (OD), particulate matter (PM), human toxicity, non-cancer effects (HT-noc), human toxicity, cancer effects (HT-c), photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx), mineral, fossil and renewable resource depletion (MFRD).



Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

- The climate change impact for rice cultivation is related to methane emission
- Additional aeration during cultivation can reduced methane emission
- Two different water managements were compared
- The additional aeration involves a reduction of climate change (from 12 to 32%)
- Arsenic decreases with additional aerations while Cadmium increases

Setting-up of different water managements as mitigation strategy of the environmental impact of paddy rice

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Abstract

Northern Italy represents the most important rice-growing district in Europe. In this area, rice is the main annual crop and the main revenues source for farmers. However, Italian climatic condition led to a traditional cultivation characterized by continuous flooding, causing emissions of methane into the atmosphere due to the organic matter fermentation in anaerobic conditions, and, consequently, a high environmental impact. The water conditions of paddy fields also affect heavy metals uptake by rice plants. In this context, this study focuses on the evaluation of environmental impact and of heavy metal content in paddy rice, and it may represent an important step in mitigating the environmental impact of rice production. In detail, this study quantifies the environmental benefits related to the adoption of an alternative water management characterised by an additional aeration period during stem elongation. To this purpose, field trials were carried out and the Life Cycle Assessment (LCA) approach was applied with a cradle-to-farm gate perspective. The potential environmental impact of the production of two rice varieties (Carnaroli and Caravaggio) was analysed in terms of 12 different impact categories and dehulled rice grain were analysed for arsenic and cadmium content.

Alternative flooding decreases CH_4 emissions in all cases evaluated (from 15% to 52%), resulting in a reduction in the climate change impact of rice cultivation (from 12% to 32%). Furthermore, the alternative water management does not influence grain yield and it reduces all the other environmental impact categories in 2 out of 4 cases. Regarding the heavy metals contents, the arsenic content in the grain decreases in all alternative scenarios, whereas the cadmium content increases, while remaining well below the legal limits.

Keywords

Life Cycle Assessment – Water management – Environmental performance - Methane emissions – Heavy metals, *Oryza sativa*. L

1. Introduction

Rice (*Oryza sativa* L. spp) is the second most cultivated cereal in the world, with a production of 755 million tons in a harvested area of 162 million hectares in 2019 (FAOSTAT, 2021). Although the largest production of rice is in Asia (China, India, Japan), this crop is also cultivated in Europe (623,000 ha in 2019) (FAOSTAT, 2021). Italy is the most important European country in terms of rice production, accounting for approximately 50% of the rice area in the continent. In more detail, 220,030 ha were dedicated to rice cultivation in Italy in 2019, with a production of 1.5 million tons (Enterisi, 2020). Thus, rice production is one of the main Italian agro-food sectors.

Despite the positive role of rice in the production areas from an economic and social point of view, the agronomic practices adopted for its cultivation can have clear drawbacks in terms of environmental impact (Leip 2007; Blengini and Busto 2009; Eshum et al., 2013; Yoo et al, 2013). Paddy fields are claimed to be responsible for approximately 11% of global anthropogenic CH_4 emissions (33–40 Tg CH4/yr) in 2000–2009 (IPCC, 2013), due to the continuous flooded cultivation. Italian climatic condition led to a traditional cultivation characterized by continuous flooding, causing huge emissions of methane into the atmosphere. In this regard, the emissions are the net result of anaerobic decomposition of organic matter in the soil (IPCC, 2006). For this reason, Italian rice production is one of the cultivation systems with the highest environmental impact. The highest methane emissions occur with long and continuous submersions, with abundant application of organic fertilizer and with the burial of the straw (Fusi et al., 2014). In detail, a previously Italian study (Bacenetti et al., 2016) reported that methane emissions account for 40-55% of environmental impact in terms of carbon footprint, for rice production. In others non-European countries methane emissions are responsible for an even greater share (up to 65%) of the impact (Roy et al., 2007; Lin and Fukushima, 2016; Nunes et al., 2017). However, alternative irrigation systems that limit the presence of a permanent water layer in the field can allow the diffusion of O_2 into the soil, thus mitigating the production of CH_4 (Xu, et al., 2015). Furthermore, since water management affects the availability of methanogenic substrates, interfering with the decomposition of the organic matter, any limitation to the permanence of water in the field can indirectly reduce CH_4 emissions by containing the presence of methanogenic substrates (Watanabe, et al., 1999). According to other studies (e. g. Nunes et al., 2016; Nunes et al., 2017), appropriate irrigation systems can reduce the carbon footprint of paddy production by

15-20%, without affecting the yield. In Italy, similar or higher reductions could likely be achieved in areas dedicated to rice cultivation, also thanks to the high specialization of rice producers, which makes plausible the adoption of alternative water management practices to continuous flooding.

For rice production, another important topic is represented by heavy metals. Heavy metals enter human body via consumption of crops grown in contaminated soil and cause serious health problems (Song et al, 2020). Anthropogenic activities, wastewater and solid waste disposal and intensive use of agrochemicals are the main responsible for paddy soil contamination by heavy metals. Heavy metals accumulating in paddy soil are taken up by rice roots which accumulate them in rice grain. In particular, rice accumulates a much higher concentration of arsenic (As) and cadmium (Cd) in the shoots and grains compared with other cereals (wheat, barley and maize) which makes rice contamination by As and Cd a global environmental health concern (Hu, et al., 2013a). Cd is a highly toxic heavy metal and it can lead to chronic toxicity disease in humans; As is also dangerous to health because it is a human carcinogen and it is easily taken in through the food chain (Hu et al., 2013). As is present in rice grain both as inorganic As (mainly arsenite) and as dimethylarsinic acid (DMA); inorganic As is generally considered to be more toxic than methylated As compounds (Arao et al., 2009). Several studies evaluated promising strategies to reduce the heavy metal content in rice grains. It has been shown that the uptake of As and Cd differs among rice cultivars and genotypes and it is also influenced by the environment (Hu et al., 2013a; Amhed et al., 2011); moreover, the practice of foliage dressing with Silicon or Selenium can reduce As and Cd content in rice grain (Liao et al., 2016). Finally, water management of paddy field affects As and Cd bioavailability in soil and their uptake by rice plants (Li et al, 2009; Zhang et al., 2019). In detail, flooding allows to reduce Cd content in different parts of rice plants, but it increases markedly As bioavailability and, thus, its absorption. In contrast, cultivation practices that include soil aeration can increase Cd content in grain, but it reduces As content. So, water irrigation system can be carefully managed to reduce the availability of these heavy metals in the soil and produce safer foods. Enterisi (2014) reported that the best trade-off for controlling simultaneously As and Cd uptake is represented by an aeration period in the middle of stem elongation and re-flooding just before booting.

Agriculture is both affected by climate change and an important contributor to greenhouse gas (GHG) emissions. World agriculture emissions within the farm gate grew by 16% between 2000 and 2017 (FAO, 2020). In detail, as mentioned above, rice fields are one of the main sources of methane emissions. For this reason, a focus on GHG reduction in rice production is a high priority (IPCC, 2019;). At the same time, in order to ensure food safety, the acceptable limit of arsenic and cadmium content in rice grains is increasingly restrictive. Therefore, it is very important to develop strategies that allow to simultaneously mitigate the carbon footprint of rice production and the content of heavy metals in the grain.

In order to evaluated environmental performances of products (processes or services), Life cycle assessment (LCA) approach is the most used methodology. It is a standardized approach and it allows to quantify several impact categories (effects on environment). Although originally it was developed for industrial system, LCA is becoming more important in agro-food sector (Fusi et al., 2014; Roy et al., 2009). In detail, there are several LCA studies for rice production (Brodt et al., 2014; Haranda et al., 2007; Kasmaprapruet et al., 2009; Lin and Fukushima, 2016; Alam et al., 2016). Specifically, there are also Italian LCA studies with the aim to detect the main environmental hotspots (processes or activities responsible for the main share of the impact) or to compare different cultivation practice in order to identify the most sustainable one (Bacenetti et al., 2020; Blengini and Busto, 2009; Fusi et al., 2017).

Although many studies have been carried out in order to demonstrate that water management can affect methane emissions from paddy field (Souza et al., 2021; Balaine et al., 2019; Zhao et al., 2019; Weller et al., 2015) and heavy metals content in rice grain (Newbigging et al., 2015; Hu et al., 2013; Tian et al., 2019), no LCA study was focused on different water management both as an impact mitigation strategy and as strategy to overcome heavy metals problem.

The aim of this study is to quantify, for rice cultivation, the environmental benefits related to the adoption of an alternative water management characterised by an additional aeration period and, at the same time, to control As and Cd uptake. To this purpose, field trials were carried out, the Life Cycle Assessment (LCA) approach was applied, and samples of rice grain were analysed with regard to the heavy metals contents. The main novelty of this study relies in the simultaneous evaluation of environmental impact and heavy metal content in paddy rice. Despite several LCA studies identified methane emissions as one of the main responsible of the impact of rice cultivation, up to now, few attention was paid on the possible benefits related to alternative water managements. Besides this, the study also considers the effect that different water management has on heavy metal contents highlighting possible trade-off between the reduction of methane emission and the increase of heavy metals. The adoption of the technique proposed in this study will allow to produce paddy rice with a lower environmental impact and safer for human health.

2 Materials and methods

2.1 Goal and scope definition

In this study, the Life cycle assessment (LCA) approach (defined in the ISO standard 14040 and 14044) was applied to rice production in Northern Italy (Lomellina area in Lombardy) during 2020. Lomellina (45°19′00″N, 8°52′00″E) together with the Provinces of Novara and Vercelli is the most important rice production area in Europe. In this area rice represents the main annual crop and the main revenues source for farmers (Enterisi, 2020). Thanks to the satisfactory economic results of rice production, in this area the rice is the main crop and there is only a limited livestock activity. Consequently, organic fertilizers such as animal manure are only rarely used and the nutrient supply is usually carried out using mineral fertilizers. The goal of this study is to quantify the environmental benefits related to the adoption of an alternative water management, while controlling the absorption of arsenic and cadmium. To this purpose, LCA was applied to compare the environmental performances of two different water managements: one based on conventional management (BS, baseline scenario), the other based on alternative management, characterized by an additional aeration period (AS, alternative scenario). In addition, in this study:

- the environmental hotspot for rice production in cases study were identified;
- samples of rice grain and soil for each experimental field were analyzed with regard to the heavy metals contents.

The results of this study could be useful for rice farmers and their associations to reduce the emission of methane and, consequently, the impact of their product without a worsening of product quality in term of heavy metal content. Besides this, the production of more sustainable rice could involve additional benefits also from an economic point of view being the “sustainability” a feature more and more required by consumers. Finally, the outcomes of this study could be useful also policy makers involved in the definition of the guidelines of integrated and sustainable crop production and/or in the setting up of the different environmental measures in the framework of Common Agricultural Policy.

2.2 Description of Rice Production system

Rice is one of the most widespread cereals in Italy especially in the eastern part of the Po Valley area. Thanks to water availability, in this area, rice is mainly cultivated in flooded fields; water is used to keep the temperature at the meristematic apex within the optimum for rice and therefore prevent cold-induced spikelet sterility in case of cold air irruptions from the Alps.

The experimental trials were carried out in four different experimental sites in Lomellina. In two sites the analysis concerned the Carnaroli variety, in the other two the Caravaggio variety was analysed. Soil is sandy loam in site 1 and site 4, and silt loam in sites 2 and 3, with organic matter varying between 1.8 % (site 2) and 1.2% (site 4). The cation exchange capacity was medium-high, with the highest value in site 4 (17 cmol(+)kg-1 clay) and the lowest in site 1 (12.5 cmol(+)kg-1 clay).

Each variety, in each site, was grown in two adjacent fields characterized by chemical-physical characteristics as similar as possible, with the same cultivation practice, varying only for water management. More in details, one aeration period of 7 days was applied in the alternative scenarios (AS); this period must be placed during the phenological stage of stem elongation, but it must be interrupted before booting. Previously studies (e. g. Enterisi, 2014), in fact, show that in the middle of stem elongation, aerobic conditions of the soil profile explored by roots lead to the reduction of arsenic content in grain. However, in order to avoid the increase of cadmium, the soil must remain flooded from the booting to waxy-ripeness. This alternative system was compared with a conventional water management (BS, baseline scenario), used by farmers.

Therefore, 8 experimental trials (4 for BS and 4 for AS) were carried out (Table 1) and the relative water management system is shown in Table 2.

Table 1 – Layout of the different experimental trials

Site	Variety	Scenario	Case
1	Carnaroli	BS	1-BS
		AS	1-AS
2	Carnaroli	BS	2-BS
		AS	2-AS
3	Caravaggio	BS	3-BS
		AS	3-AS
4	Caravaggio	BS	4-BS
		AS	4-AS

Table 2: Main informations about the two compared water managements.

Variety	Case	Flooding start	Aerations	Flooding end
Carnaroli	1-BS	19/06		30/08
	1-AS	27/06	1) From 29/06 to 3/07	30/08
Carnaroli	2-BS	7/04		15/09
	2-AS	7/04	1) From 17/06 to 27/06 2) From 25/07 to 4/08	15/09
Caravaggio	3-BS	7/04		15/09
	3-AS	7/04	1) From 17/06 to 27/06 2) From 25/07 to 4/08	15/09
Caravaggio	4-BS	27/04	1) From 9/05 to 28/05	12/08
	4-AS	27/04	1) From 9/05 to 28/05 2) From 24/06 to 1/07 3) From 17/07 to 23/07	12/08

In general, the rice production system includes several common operations, which can be divided into 3 sections:

- Section 1: soil tillage and sowing. Ploughing is the main processing of the paddy field. It is performed with a plough (30 cm deep), in order to incorporate into the soil the straw from the previous year. Later, a specific operation for the preparation of the paddy field is leveling, using laser-levelers. This is an operation to maintain the perfect horizontality of the cultivation plan. Then, the paddy field is prepared for sowing by harrowing (with a rotary harrow). Usually, organic or mineral fertilization is carried out before sowing. The sowing can be performed in non-flooded or in flooded fields, using a precision seeder.
- Section 2: crop management. In this section there are two fundamental operations: the chemical control of weeds and diseases and fertilization. Several pesticides and mineral fertilizers can be applied.
- Section 3: harvesting and storage. Approximately 2 weeks before the harvest, the flooding is stopped. The harvesting operations are carried out by combine harvester when the moisture content of rice grain is 20-30% (depending on climatic conditions). Paddy rice is loaded into farm trailers coupled with tractors, and then it is transported to the farm where it is dried to a humidity of 14% by means of a farm dryer. The straw is left on the ground.

2.3 Functional unit

The functional unit (FU) is defined as a quantified performance of a product system to be used as a reference unit in a LCA (ISO 14040, 2006). The main function of the rice cultivation is the production of grains. Even if straw is the coproduced it is not harvested due to the lower/no economic value. Being the straw left on the soil, the grains is the only useful product, and it can be quantified easily in term of rice grains mass. Previously published LCA studies focused on rice grain production (e.g. Bacenetti et. al., 2016; Fusi et. al., 2017; Fusi et al., 2014; He et al., 2018;) selected the mass of rice grain at commercial moisture (14%) as FU. In this study, taking into account that an additional evaluation was carried out about the heavy metal content, the selected functional unit was 1 ton of rice grains at the commercial moisture and respecting the legal limits with regard to the content of arsenic and cadmium.

2.4 System boundary

Concerning the system boundary, a "from cradle to farm gate" approach was applied. Consequently, the system boundary includes all the activities carried out from the extraction of the raw materials to the drying of grains (Figure 1). The following aspects were considered: i) extraction of raw materials (e.g. fossil fuels, metals and minerals); ii) manufacture, maintenance and disposal of the capital goods (e.g. tractors, agricultural machines, shed and grain dryer); iii) production of the different inputs (fertilizers, pesticides, electricity, diesel, etc.); iv) emissions related to the use of input factors (e.g, emissions due to fertilizers application, diesel fuel emissions related to diesel combustion in the tractor engine).

No Allocation was carried out because straw is left into the field and it is incorporated in during primary soil tillage operations carried out in the first spring after the harvesting.

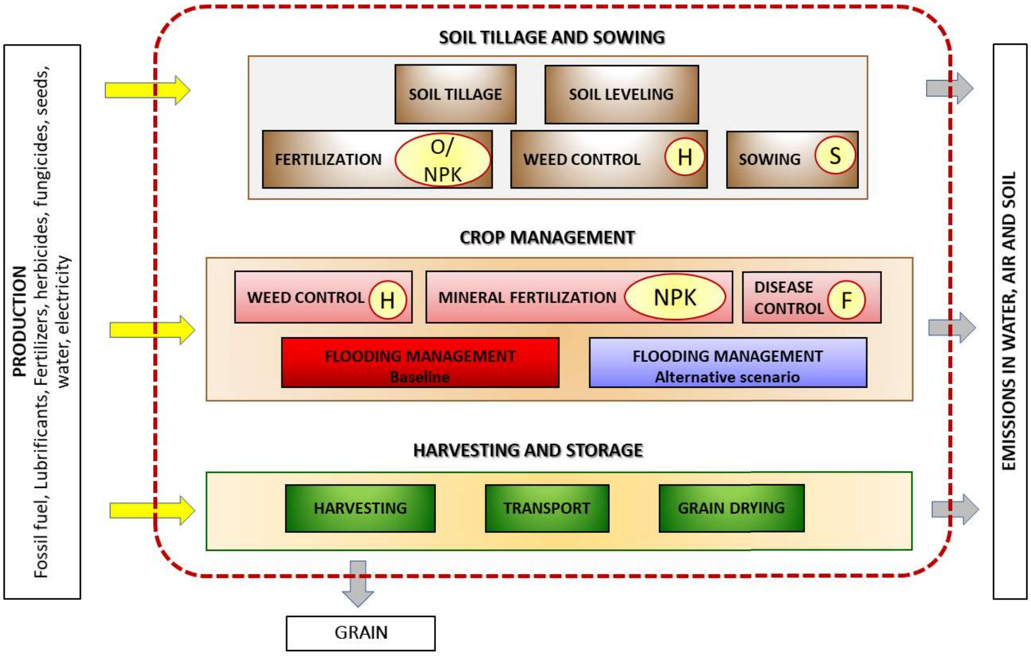

Figure 1: System boundaries. O: organic fertilizer; NPK: mineral fertilizer; H: herbicide; S: seed; F: fungicide.

The emission sources considered refer to: N and P compounds emission mainly related the fertilization, emissions of methane due to the organic matter decomposition in anaerobic conditions and emissions of pollutant due to the combustion of fuels in the machine engines.

According to the Product Category Rules for "Arable crops" (Environdec, 2014) and considering that the fields are dedicate to rice cultivation by more than 20 years, no changes in the soil organic carbon content were considered.

2.5 Inventory data collection

Primary data were collected by means of interviews with the farmers and surveys in the paddy fields during the trials. Secondary data were obtained from database for LCA studies (e.g., Ecoinvent® 3.6), scientific literature or were estimated using specific models.

The information about the cultivation practice (sequence of field operations, timing, working time, characteristics of tractors and operative machines use, agricultural inputs (e.g., seeds, fertilizers, plant protection products, fuels, etc.) were obtained directly from the farmers during the interviews (from Table 3 to 6).

Table 3: Cultivation practice: field operations and production factors consumed – Carnaroli – 1-BS, 1-AS.

Section	Operation	Input other than diesel	Amount (· ha^{-1})
(1) **Soil tillage and sowing**	Ploughing		
	Levelling		
	Mineral fertilization	Mineral fertilizer N.P.K 0.16.25	290 kg
	Weed control pre seeding	Glyphosate	4 kg
	Seeding + localized fertilization	Seeds Humus start 11.50.0	180 kg 40 kg
(2) **Crop management**	Weed control post germination (I)	Clomazone Oxadiazon	126 g 709 g
	Weed control post germination (II)	Cyhalofop-butyl Profoxydim Methyl oleate/Methyl palmitate	300 g 100 g 174g
	Weed control post germination (III)	Penoxsulsm Halosulfuron-methyl MCPA	40 g 28 g 30 g
	Mineral fertilization (I)	Delfan 5.0.0 Folistar 15.4,5.3	0.37 kg 2.2 kg
	Mineral fertilization (II)	Mineral fertilizer NPK 23.0.30	180 kg
	Disease control (I)	Ureic nitrogen Folistar 15.4.5.3 Azoxystrobin Difenoconazole	0.88 kg 2,21 kg 180 g 112 g
	Mineral fertilization (III)	Mineral fertilizer NPK 23.0.30	200 kg
	Disease control (II)	Azoxystrobin	250 g
(3) **Harvesting and storage**	Harvesting		
	Transport		
	Drying		Water Evaporated: BS: 629 kg AS: 807 kg

Table 4: Cultivation practice: field operations and production factors consumed – Carnaroli – 2-BS, 2-AS.

Section	Operation	Input other than diesel	Amount (· ha^{-1})
(1) Soil tillage and sowing	Minimum Tillage		
	Harrowing		
	Organic fertilizer	Organic nitrogen (BS) Superguanoxy[a] (AS)	40 kg 475 kg
	Weed control (I)	Glifosate Ammoniacal nitrogen P_2O_5	1.2 kg 45 g 255 g
	Weed control (II)	Oxadiazon	304 g
	Seeding	Seeds	180 kg
(2) Crop management	Weed control post germination	Penoxsulam MCPA Bensulfuron-methyl Metsulfuron-methyl Halosulfuron-methyl Ammoniacal nitrogen P_2O_5 Lambda-Cyhalotrin	40 g 200 g 28 g 1.1 g 23 g 30 g 170 g 12 g
	Mineral fertilizations	Mineral fertilizer N/K 21.27 Potassium chloride	100 kg 150 kg
	Disease control (I)	Florpyrauxifen-benzyl (BS) Methyl oleate/Methyl palmitate (BS)	25 g 349 g
	Disease control (II)	Azoxystrobin	250 g
(3) Harvesting and storage	Harvesting		
	Transport		
	Drying		Water Evaporated: BS: 685 kg, AS: 557 kg

[a] Superguanoxy composition: organic N 4%; P_2O_5 10%; K_2O 5%; MgO 2%; SO_3 5%; CaO 8%; Organic carbon 15%; Humus organic matter 30%.

Table 5: Cultivation practice: field operations and production factors consumed – Caravaggio – 3-BS, 3-AS.

Section	Operation	Input	Amount (· ha^{-1})
(1) Soil tillage and sowing	Ploughing		
	Levelling		
	Harrowing		
	Mineral fertilization	Mineral fertilizer N.P.K 12.0.12	600 kg
	Weed control (I)	Fluefenacet	42 g
	Weed control (II)	Oxadiazon Bensulfuron-methyl Metsulfuron-methyl	304 g 31 g 1.2 g
	Seeding	Seeds	180 kg
(2) Crop management	Weed control post germination	Penoxsulam Florpyrauxifen-benzyl MCPA Lambda-Cyhalotrin	40 g 19 g 200 g 12 g
	Mineral fertilization	Mineral fertilizer N/K 21.27	100 kg
	Disease control (I)	Azoxystrobin	250 g
(3) Harvesting and storage	Harvesting		
	Transport		
	Drying		Water Evaporated: BS: 324 kg, AS: 308 kg

Table 6: Cultivation practice: field operations and production factors consumed – Caravaggio – 4-BS, 4-AS.

Section	Operation	Input	Amount (· ha^{-1})
(1) Soil tillage and sowing	Ploughing		
	Levelling		
	Harrowing		
	Weed control (I)	Oxadiazon Cycloxydim	380 g 300 g
	Seeding	Seeds	180 kg
(2) Crop management	Weed control post germination	Profodydim Florpyrauxifen-benzyl Methyl oleate/Methyl palmitate Lambda-Cyhalotrin	76 g 30 g 154 g 2 gr
	Mineral fertilization (I)	Ureic Nitrogen	74 kg
	Mineral fertilization (II)	Mineral fertilizer 16.0.30	150 kg
	Disease control (I)	Azoxystrobin Difenoconazole	240 g 150 g
(3) Harvesting and storage	Harvesting		
	Transport		
	Drying		Water Evaporated: BS: 566 kg, AS: 450 kg

In order to verify that the alternative water management does not modify the morphological characteristics and the components of yield, dedicated morphological measurements (number of panicle per plant, main culm height, diameter of the major and minor axis of the culm base, harvest index, weight of 1000 seeds) were carried out on 20 plants randomly sampled from each experimental field. In addition, the number of panicles per square meter was determined in three random points of each experimental field.

In detail, the harvest index obtained was used to estimate the straw produced and buried in the soil; the morphological differences found between plants cultivated in baseline scenarios and those cultivated in the respective alternative scenarios were compared using one-way analysis of variance (ANOVA) after checking the assumptions of normality and homogeneity of variance. Moreover, the arsenic and cadmium content in the experimental fields and in the dehulled grain was analysed by inductively coupled plasma mass spectrometry (Bruker Aurora M90 ICP-MS, ICP Mass Spectrometer) and compared. In detail, for the soils, the analysis was carried out by taking 3 soil samples for each experimental field, while for the grain, the analysis was performed on the grain obtained from a sample of 5 kg for each experimental field supplied directly by producers, after carrying out the dehulling process. Finally, the fraction of inorganic arsenic in the dehulled grain was also analysed via inductively coupled plasma mass spectrometry and high-performance liquid chromatography (HPLC-ICPMS).

For the different 8 paddy fields, the grain yield (Table 7) was measured by means of the farm weighbridge, whereas the straw production was estimated considering the Harvest Index (HI, ratio among the grain dry mass and the global above ground dry biomass) evaluated through the field measurements described above.

Table 7: Grain yield at commercial moisture (14%).

Variety	Case	Grain yield (t ha^{-1}, 14% moisture)	Variation %
Carnaroli	1-BS	6.90	
	1-AS	6.99	+1.3%
Carnaroli	2-BS	5.21	
	2-AS	4.23	-18.8%
Caravaggio	3-BS	6.65	
	3-AS	6.32	-4.9%
Caravaggio	4-BS	6.38	
	4-AS	6.58	+3.1%

The methane emissions were estimated using the emission factors and the methodology proposed by the IPCC (IPCC, 2006). The default methane emission factor (1.30 kg CH4·ha^{-1}·day^{-1}) was used and scaled using a scaling factor for: i) water regime before and during cultivation, ii) the number of aeration periods, iii) the application of organic matter into the soil (organic fertilizer and straw); iv) the timing of straw incorporation; v) the duration of flooding. For each rice variety, between the two scenarios the main differences refer to flooding duration, the number of aerations and the amount of straw.

The methane emissions in different scenarios (see. Table 8) range from a minimum of 65.97 kg·ha^{-1} in farm 1 AS, to a maximum of 257.95 kg·ha^{-1} in Farm 2 BS.

Table 8: Methane emissions during the rice cultivation in the different experimental fields.

Variety	Case	Number of aerations	CH_4 emissions (kg ha $^{-1}$)	Variation %
Carnaroli	1-BS	0	129.19	
	1-AS	1	65.97	-49%
Carnaroli	2-BS	0	257.95	
	2-AS	2	125.03	-52%
Caravaggio	3-BS	0	257.13	
	3-AS	2	131.26	-49%
Caravaggio	4-BS	1	101.2	
	4-AS	3	85.98	-15%

Nitrogen emissions (nitrate leaching, ammonia volatilization, and nitrous oxide emissions in atmosphere) were computed in the following ways:

- Ammonia volatilization: using emission factors suggested by EMEP/CORINAIR (EMEP/EEA, 2019);
- N_2O and NO direct emissions: using emission factors calculated by Bouwnan, et al. (2002);
- N_2O indirect emissions: using emission factors suggested by IPCC (IPCC, 2006);
- Nitrate emissions (leaching and runoff): using emission factors suggested by IPCC (IPCC, 2006).

Phosphate emissions in water were calculate following Prahsun (2006).

Pesticide emissions were estimated according to the Product Category Rules for Arable Crops (Environdec, 2014) and consequently, the 100% of active ingredient of pesticides was considered released into the soil.

For the different mechanized field operations carried out during the cultivation, the diesel fuel consumption was estimated considering the power requirements by the operative machines, their effective field capacity, and the soil characteristics according to Lovarelli and Bacenetti (2017).

Background data regarding the production of the different production factors used (fertilizers, seeds, pesticides, fuels, energy, agricultural equipment, dryer) were retrieved from the Ecoinvent database v3.6 (Weidema et al., 2013; Moreno Ruiz et al., 2018).

2.6 Life Cycle Impact Assessment (LCIA)

Using the midpoint ILCD method (Wolf et al., 2012) and a specific software, the inventory data collected were processed to quantify the following potential environmental impacts:

- climate change (CC, expressed as kg CO_2 eq.),
- ozone depletion (OD, expressed as kg CFC-11 eq.),
- particulate matter (PM, expressed as kg PM2.5 eq),
- human toxicity, non-cancer effects (HT-noc, expressed as CTUh),
- human toxicity, cancer effects (HT-c, expressed as CTUh)
- photochemical ozone formation (POF, expressed as kg NMVOC eq.),
- terrestrial acidification (TA, expressed as molc H+ eq.),
- terrestrial eutrophication (TE, expressed as molc N eq.),
- freshwater eutrophication (FE expressed as kg P eq.),
- marine eutrophication (ME, expressed as kg N eq.),
- freshwater ecotoxicity (FEx, expressed as CTUe),
- mineral, fossil and renewable resource depletion (MFRD, expressed as kg Sb eq.).

3. Results

3.1. Environmental impacts

Figure 2 and 3 report the results of the contribution analysis for the Carnaroli variety cultivation for case 1 while the results for the other cases are reported as Supplementary Material. For the different evaluated impact category, the contribution analysis identifies the relative contribution of the different inputs and outputs to the overall impact. The results of the contribution analysis are similar for all the different cases. In fact, there are no relevant differences between the two varieties; furthermore, also the water management does not influence the contribution analysis, with the exception of the impact share of methane emissions in Climate Change. In all alternative scenarios, the contribution of the methane emissions is always lower than in the respective baseline scenario. Anyway, methane emissions always represent the main hotspot of the CC: the impact share ranges from 50 to 75% in the baseline scenarios and from 35% to 62% in the alternative scenarios. In detail, cases 2 and 3 report the highest share of CC due to methane emissions (75% 2-BS, 62% 2-AS; 70% 3-BS and 55% 3-AS). The amount of methane emitted is also the highest in the same cases (257.95 kg ha^{-1} 2-BS versus 125.03 kg ha 2-AS and 257.13 kg ha^{-1} 3-BS versus 131.26 3-AS due to the longer duration of the flooding (147 days). However, in Caravaggio variety in case 4 (4-BS and 4-AS), the contributions analysis shows similar results also in CC because producer carried out an aeration period also in BS. In this situation, methane emissions account for 49% in BS and for 46% in AS.

Besides CC, methane emissions have an impact only in photochemical ozone formation , which ranges from 7% to 18% in the BSs and from 4% to 10% in the ASs.

The emissions of N and P compounds mainly related to the fertilizer application (nitrate leaching, nitrous oxide production, ammonia volatilization and phosphorus run-off) affect several categories: Particulate Matter (from 39% to 72% for both BSs and ASs), terrestrial acidification (from 72% to 92% both for BSs and ASs), terrestrial eutrophication (from 77% to 94% for both BSs and ASs), freshwater eutrophication (from 39% to 52% for BSs and from 40% to 58% for ASs) and marine eutrophication (from 87% to 94% for both BSs and ASs).

The mechanization of field operations (that groups impact of diesel fuel production and consumption with manufactory, maintenance and disposal of tractors and implements) plays a key role on HT-noc (from 57 to 77% for all cases analyzed) and on MFRD (from 21% to 57% for both BSs and ASs).

Pesticide emissions only affect FEx and never exceed 21% in any of the cases analyzed. Finally, drying processing contributes to the impact especially in OD (from 24% to 33%) and in HT-c (from 13 to 34%).

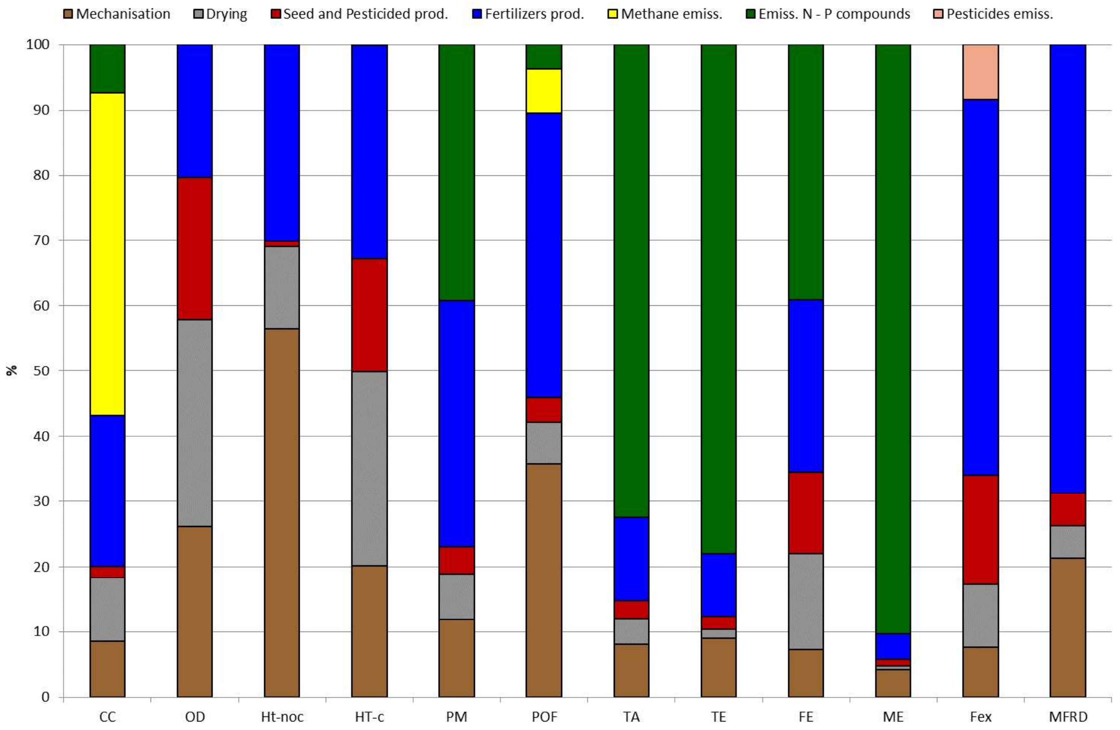

Figure 2: Relative contributions to the overall environmental impact for Carnaroli, 1-BS.

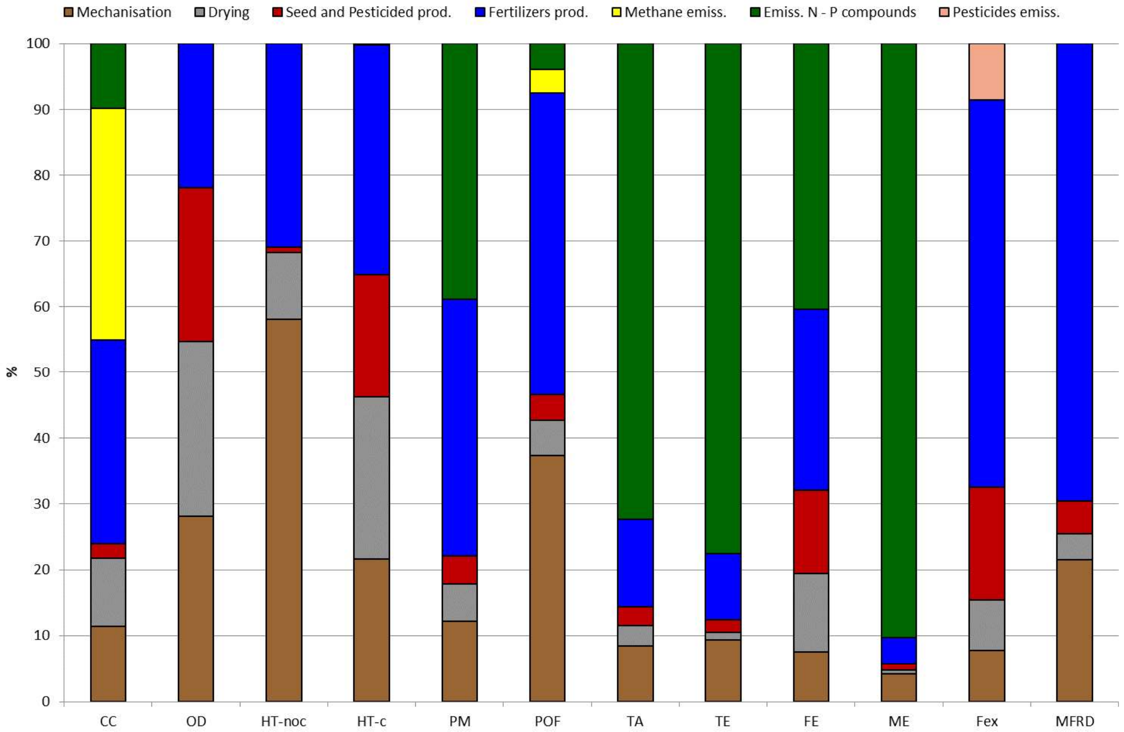

Figure 3: Relative contributions to the overall environmental impact for Carnaroli, 1-AS.

Table 9 reports the absolute potential environmental impact for all the evaluated cases, while table 10 shows a focus on Climate Change. In table 9 higher values are highlighted in red; for progressively lower impacts, it goes to orange-yellow and then green. In general, it is not possible to say which variety has the lowest impact. Caravaggio in 4-BS and 4-AS is the best in terms of environmental impacts, with the exception of 4 impact categories (PM, TA, TE e ME) where the less impacting case is 3-BS for PM, 1-AS for TA and TE and 2-AS for ME. In fact, these impact categories are negatively affected by the high fertilizations which result in higher N and P compound emissions.

Table 9: Potential environmental impact for all scenarios (FU = 1 ton of rice grain at commercial moisture; higher values are highlighted in red; for progressively lower impacts, it goes to orange-yellow and then green

		Case 1 - Carnaroli		Case 2 - Carnaroli		Case 3 - Caravaggio		Case 4 - Caravaggio	
Impact category	Unit	1-BS	1-AS	2-BS	2-AS	3-BS	3-AS	4-BS	4-AS
CC	kg CO_2 eq	944	743	1659	1187	1373	940	890	781
OZ	mg CFC-11 eq	44.97	41.31	48.93	56.22	42.55	44.46	35.30	32.07
HT-noc	CTUh/1000	0.208	0.199	0.170	0.202	0.173	0.182	0.154	0.145
HT-c	CTUh/1000	0.019	0.017	0.018	0.021	0.013	0.014	0.014	0.013
PM	kg PM2.5 eq	0.389	0.373	0.446	0.422	0.352	0.365	0.648	0.618
POF	kg NMVOC eq	2.788	2.626	2.759	2.931	2.802	2.744	2.137	2.019
TA	molc H+ eq	9.64	9.18	15.32	13.29	9.59	9.84	23.27	22.23
TE	molc N eq	40.23	38.46	66.89	57.66	41.83	42.93	102.69	98.26
FE	kg P eq	0.146	0.140	0.142	0.198	0.106	0.111	0.112	0.105
ME	kg N eq	8.054	7.815	7.478	6.800	7.421	7.689	9.801	9.387
FEx	CTUe	4139	4000	3434	4091	3112	3266	2646	2505
MFRD	g Sb eq	14.27	13.94	8.02	9.58	7.88	8.27	6.59	6.28

Respect to BS, CC decreases in all alternative scenarios evaluated (-25% and -28% for Carnaroli variety, -32% and -12% for Caravaggio variety). More in details, for Carnaroli in case 1, CC decreases from 944 to 743 kg CO_2 eq /FU with a 49% reduction in methane emissions (129 kg ha^{-1} 1-BS versus 65 kg ha^{-1} in 1-AS), while for Carnaroli in case 2, CC ranges from 1659 kg CO_2 eq/FU in 2-BS to 1187 kg CO_2 eq /FU in 2-AS (emissions of CH_4 from 257.95 kg ha^{-1} to 125.03 kg ha^{-1}, -52%). For Caravaggio, CC is 1373 kg CO_2 eq/FU for 3-BS and 940 CO_2 eq/FU for 3-AS (emissions of CH_4 257.13 kg ha^{-1} in 3-BS and 131.26 kg ha^{-1} in 3-AS, -49%). Finally, in the last case, CC decreases from 890 (4-BS) to 781 (4-AS) kg CO_2 eq/FU, with a 15% reduction in methane emissions (101.2 kg ha^{-1} in 4-BS and 85.98 kg ha^{-1} in 4-AS). In this case, the producer carried out an aeration also in BS, so methane emissions and, consequently, CC were already low in BS and the effect of the additional aeration period in AS is reduced.

Table 10: Focus on Climate Change (CC) results

Variety	Case	Number of aerations	Emission of CH_4 (kg CH_4 ha^{-1})	Variation %	CC (kg CO_2 eq)	Variation %
Carnaroli	1-BS	0	129.19		995.9	
	1-AS	1	65.97	-49%	742.7	-25%
Carnaroli	2-BS	0	257.95		1658.6	
	2-AS	2	125.03	-52%	1187.1	-28%
Caravaggio	3-BS	0	257.13		1373	
	3-AS	2	131.26	-49%	940	-32%
Caravaggio	4-BS	1	101.2		890	
	4-AS	3	85.98	-15%	780.8	-12%

Figure 4 shows the comparison between the potential environmental performances of the two different cultivation practices for all the evaluated impact category. Except than for CC, the impact variations are mainly related to the variation of the yield. In fact, as explained before, methane emissions impact only for the CC and for the photochemical ozone formation (POF).

The alternative water management (ASs cases) always involves a reduction of CC independently by yield and other operation characterizing the cultivation practices: more in details, comparing BS and AS, in the scenario where an additional aeration is performed:

- for Carnaroli in case 1 (1-AS), CC decreases by 25% and also the other impact categories are reduced (from -2% for MFRD to -8% for OD), mainly due to the slightly yield increase (+1.3%);
- for Carnaroli in case 2 (2-AS), despite a considerable yield reduction (18.8%, mainly related to weeds), the CC is lower by 28%. Contrarily than for CC, the other impact categories increase from 6% for POF, to 39% for FE.
- for Caravaggio case 3 (3-AS), CC was reduced of -32% but, the yield reduction (4.9%) leads to a small increase in the other impact categories (from 3% for A and TE to 5% for HT-noc, FE, FEx and MFRD).
- for Caravaggio in case 4 (4-AS), CC is reduced (12%) and, thanks to the yield increase (3.1%) also all other categories are decreased (-4% for A, TE, ME, -5% for PM, FEx and MFRD, - 6% for HT-noc, POF and FE and -9% for OD and HT-c).

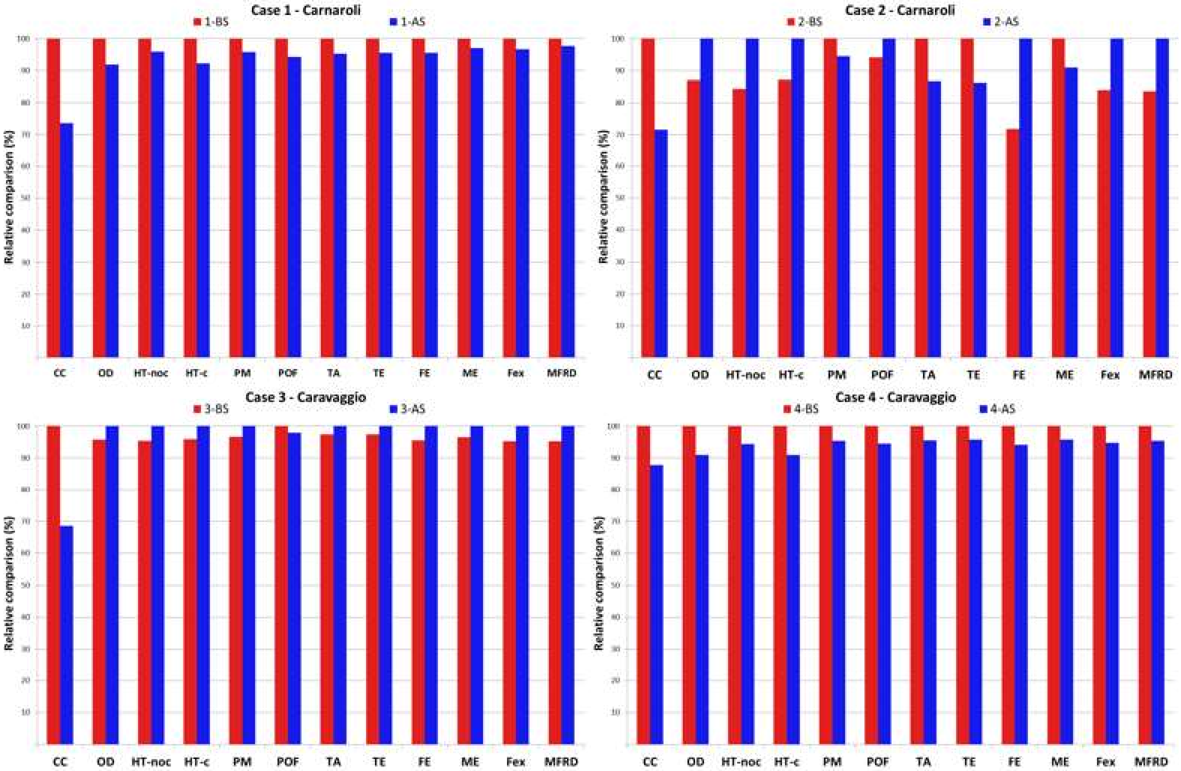

Figure 4: Comparison between two scenarios within same case.

3.1.1 Sensitivity analysis

A detailed sensitivity analysis was conducted on key parameters to explore their impact on the environmental performance of the system. In detail, the following aspects were considered:

- grain yield taking into account the yield recorded at the farm weighbridge and the coefficient of variation (±15%) calculated considering the productive performance in the different sites;
- the harvest index considering the minimum and the maximum values measured in the different sites (instead of the one specifically measured for the case under evaluation). The harvest index is related to the amount of straw produced and incorporate into the soil. Consequently, a higher harvest index involves lower methane emission because less

straw is incorporated in the soil. No changes were done for the cases corresponding to minimum or the maximum harvest index;

- the minimum and the maximum scaling factor for water management (SFw) during the cultivation. In this regard, the methane emissions were recalculated instead of with the default SFw using the minimum and the maximum values reported by the IPCC (2006). No changes were introduced for those cases where no aerations are performed and, consequently, the SFw is equal to 1.

The results of the sensitivity analysis, reported in the Supplementary material (Tables S1-S4) show how the parameter most affecting the environmental performance is the grain yield. Being the grain yield directly related to the FU and affecting also other processes like transport and drying, the yield variation considered (±15%) involves changes for all the evaluated environmental impact categories. The higher variation is achieved for POF, TA, TE and ME while the lower for OD (that is the impact category were the drying plays the major role). Unlike than for yield, the variation of the harvest index and of the SFw influences only the methane emission and, consequently, affects only those impact categories affected by methane emissions (CC and POF). About the harvest index, the scale of impact variation depends on the value measured for the specific case. The impact variation is small if the measured value is close to the min/max harvest index while it is higher if the difference between the considered harvest indexes is wider. However, the changing of the harvesting index involves modest impact variations, always < 6% for CC and < 2% for POF. When in the assessment of methane emissions, for the SFw a different value is considered respect to the default one, the effect on CC and POF is not negligible. In particular, for CC, the impact variation is higher than the one highlighted before for yield and ranges from -13.2% to +16.8%. However, it is interesting underline that, these impact variations of CC are, for 3 of the 4 cases, lower than the impact reduction achieved with the introduction of an additional aeration period.

3.2. Heavy metals content

Table 11 and table 12 report the arsenic and cadmium content in the dehulled grain and soil samples, respectively As regards arsenic, the values refer to inorganic arsenic for grain and total arsenic for soils. Inorganic As is generally considered to be more toxic than methylated As compounds (Arao et al., 2009), in fact the limit imposed by official regulation refers to this form of As (0.25 mg/kg, Commission regulation, 2015). As expected, the additional aeration period affects the heavy metal content in both grain and soils. Inorganic arsenic in the dehulled grain decreases in all alternative scenarios (-11% and -4% for Carnaroli and -27% and -14% for Caravaggio) and it is below the legal limit in all cases analysed;Cd content increases in 3 out of 4 cases (+75% in 2-AS, +66% in 3-AS and +97% in 4-AS). Although these percentage increases are considerable it should be noted that the absolute contents remain very low and below the legal limits in force in the 2020 season (0.2 mg/kg, Commission regulation, 2006): 0.021 mg/kg in 2-AS, 0.02 mg/kg in 3-AS and 0.067 mg/kg in 4-AS. Recently, the European Commision has updated cadmium content limit, lowering it to 0.15 mg/kg. It is important to note that the values in this study are also below the new limit. Regarding heavy metals content in soils, the Cd content is never detectable (in line with the low levels found in the grains), while As content presents a non-specific trend. In particular, the trend are in line with expectations (lower As in the plots with aeration periods) only in site 1 (percentage not measurable) and site 2 (-27%), while the other two cases show an opposite trend (+24% in case 2, +13% in case 3).

Interestingly, for arsenic, the content in rice grain is not correlated with the content in the soil. In fact, the soil with the highest arsenic concentration is in site 2 (7.4 and 9.2 mg/kg for 2-BS and 2-AS), but the grain has an arsenic content of 0.126 in 2-BS and 0.121 mg/kg in 2-AS. On the contrary, rice grain in site 4 has an arsenic concentration of 0.199 and 0.171 mg/kg respectively in 4-BS and 4-AS, although the soil content is relatively low (3.5 and 2.5 mg/kg). Furthermore, the concentration of arsenic in soils is very different between site 1 (1.4 and <1 mg/kg for 1-BS and 1-AS) and site 2 (7.4-9.2 mg/kg), but the content in the grain is similar (0.116 and 0.104 in 1-BS and 1-AS, 0.126 and 0.121 in 2-BS and 2-AS). Finally, Caravaggio in site 3, has a relatively high arsenic content compared to the other cases (0.183-0.133 mg/kg for 3-BS and 3-AS), in relation to the soil content (1.6-1.8 mg/kg).

In general, in this study, Caravaggio variety has a higher arsenic content than Carnaroli.

Table 11: As and Cd content in dehulled rice grain.

Variety	Case	Inorganic As (mg/kg)	Variation %	Cd (mg/kg)	Variation %
Carnaroli	1-BS	0.117±0.023		0,011±0,003	
	1-AS	0.104±0.021	-11%	0,008±0,002	-27%
Carnaroli	2-BS	0.126±0.025		0,012±0,003	
	2-AS	0.121±0.024	-4%	0,021±0,005	+75%
Caravaggio	3-BS	0.183±0.037		0,012±0,004	
	3-AS	0.133±0.027	-27%	0,02±0,003	+66%
Caravaggio	4-BS	0.199±0.040		0,034±0,007	
	4-AS	0.171±0.034	-14%	0,067±0,0012	+97%

Table 12: As and Cd content in soil samples.

Variety	Case	Total As (mg/kg)	Variation %	Cd (mg/kg)
Carnaroli	1-BS	1,4		<1
	1-AS	<1	n.d.	<1
Carnaroli	2-BS	7,4±0,1		<1
	2-AS	9,2±0,2	+24%	<1
Caravaggio	3-BS	1,6		<1
	3-AS	1,8	+13%	<1
Caravaggio	4-BS	3,4±0,1		<1
	4-AS	2,5±0,1	-27%	<1

4. Discussion

In this study thanks to LCA, the environmental consequences related to different water management in rice cultivation were evaluated. Besides this the main hotpots of the environmental profile of paddy rice cultivation and the environmental benefits related to the adoption of alternative flooding management were quantified. In detail, the Climate Change impact of rice cultivation is mainly due to methane emissions from the flooded field.

The comparison among the results of different LCA studies is not always possible mainly because different system boundary and functional unit are used, different methodological assumptions are done (e.g., about multifunctionality issues, model used to estimate the emission etc.) and few information about rice varieties is reported. Despite this, the contributions analysis in this study shows similar results to other LCA studies focused on rice. In particular, also Fusi et al., (2014), Bacenetti, et al., (2016) and He et al., (2028) identified methane emissions as the main responsible for the climate change. Hokazoko and Hayashi (2012) and Mungkung et al., (2020) identified the emission related to fertilization were the main contributor to acidification and eutrophication. Finally, also Blengini and Busto (2009) and Drocurt et al. (2012) identified fertilizer applications, methane emissions and the emissions related to fertilizers application as the main hotspots for paddy rice cultivation. Except than for methane emission, in term of contribution analysis, there are no differences between the different items in for baseline and alternative scenarios. In fact, the alternative water management deeply affects only CC, has a limited impact on POF while does not influence all the other evaluated impact category. Having a no or/limited effect on grain yield, the introduction of an additional aeration is an effective mitigation solution for CC.

The cultivation system based on sowing in flooded-field and a continuous flooding of the paddy fields considerably increases emissions of CH_4 from the soil, while the addition of aerations can mitigate the emissions. Strictly anaerobic soil conditions represent a prerequisite for methanogenic activity and the positive correlation between methane emissions and flooded soil suggests that the permanence of a layer of water can affect methane production (Peyron et al., 2016). As expected, and demonstrated in other studies (Feng et al., 2021; Leon et al., 2021; Wassmann et al., 2010; Li et al.,2006), also in this study, alternative water management allows to lower methane emissions: in three out four alternative scenarios methane emissions have practically halved (-49% in 1-AS, -52% in 2-AS, -49% in 3-AS) and, consequently, the impact share relating to methane emissions also decreased. However, it is important to highlight that the methane emissions, in this study, were estimated using IPCC model (2006). Therefore, the results should be confirmed through a direct survey, with direct detection tools, to measure the actual emissions in the field.

Previously studies in other countries (e.g., Nunes et al., 2016; Nunes et al., 2017; Setyanto et al., 2018) show that an appropriate management of irrigation water can reduce the CC of paddy rice production by 15-20%, without any influence on yield. On the contrary, in other studies, it was reported that an alternative water management (with one or more aeration periods or alternating wetting and drying) causes a reduction in grain yield (Xu et al., 2015; Feng et al., 2021; Carrijo et al, 2017; Bacenetti et al., 2016). This study shows that higher reductions of CC can be achieved (up to 32%) by the introduction of one additional aeration period highlighting how the water management can be an effective mitigation solution for CC. Moreover, in this study, alternative water management does not affect rice grain yield (as long as during flowering water level is keep high enough to protect the spikelets from cold air).

Nevertheless, alternative water management, that can mitigate methane emissions, can also involve higher N_2O emissions (Zou, et al., 2007; Peyron et al., 2016) being soil water status is the major factor influencing N_2O emission during the rice-growing season (Wang, et. al., 2011). In detail, Wang et. al., (2011) report that season N_2O emission from fields with mid-season drainage are higher than those from continuously flooded fields. Frequent alternations in the redox conditions of the soil as a result of dry-wet transitions increase up to N_2O, favouring the nitrification and denitrification processes responsible of the production of dinitrogen monoxide. This could reduce the benefits of methane mitigation achieved by introducing aeration periods. Therefore, future studies will have to simultaneously consider methane and nitrous oxide emissions to determine the right trade-off to minimizing carbon footprint of rice cultivation systems. Generally, to improve the environmental performance of rice production, different strategies could be integrated. For example, in addition to changing water management, straw could be collected to reduce methanogenic substrates in the soil and lower methane emissions (Fusi et al 2014; Maneepitak et al., 2019). Moreover, new solutions should be developed to achieve the right trade-off also between the various impact categories: such as, to lower the impact of the use of fertilizers, more organic fertilizers could be used, taking into account that the CC would increase. In this way, a mitigation of the total impact could be achieved. In addition, also minimum tillage and sod sowing techniques could reduce the environmental impact of rice production, as they are characterized by lower energy inputs. However, in this regard, it should be ensured that there is no significant loss of yield.

The results of the analysis of heavy metals content in grain confirm that alternative water management modifies the absorption of heavy metals, as reported in other studies (Hu, et al., 2013; Liao, et al., 2016; Arao, et al., 2009). In particular, it is an effective strategy to lower the inorganic As content in rice grain, keeping the cadmium content below the legal limit. However, as shown in tables 11 and 12, there is a lot of variability between the variations of the heavy metals contents, in both grain and soil. This is because, as reported in other studies (e.g. Mei et al., 2020; Yang et al., 2021) , the bioavailability of heavy metals in the soil and their absorption are very complex processes. Certainly the water management of the paddy field plays a key role in the growth of tice and in the control of As and Cd concentrations in the grain. Changes in water conditions can simultaneously alter soil pH and Eh and therefore influence the bioavailability of As and Cd in soils (El-Naggar et al., 2018, 2019). In addition, Pinson et al., (2015), reported that the ability of rice to accumulate As and Cd is related to genetic factors, so different accumulation characteristics depend on the different genotypes and the different varieties. This study is in agreement with this statement since the Caravaggio variety always has a higher heavy metal content, regardless of soil contamination, than Carnaroli. Nevertheless, in this study, the arsenic and cadmium content in the analysed grain is always below the legal limits.

This means that in the cases studied the problem of the accumulation of heavy metals was not relevant, but this study shows that it is always necessary to evaluate the content of arsenic and cadmium in rice grain when applying a water management other than the conventional one. In the specific case, thanks to the results of the analysis of the metals and the non-variation of the yield, future analyses could be focused on inserting more aeration periods, further mitigating methane emissions. It is certain that in areas where the problem of heavy metals is relevant, it is necessary to consider all the advantages and disadvantages that coul derive from an alternative water management.

Therefore, this study highlights the importance of considering the effect of paddy water management on the uptake of heavy metals and their translocation to the grains. Beside mitigating the environmental impact, food safety is indeed another key issue in paddy rice production.

5. Conclusions

The research for cultivation practices aimed at reducing the impact of Climate Change is constantly evolving because agricultural activities are responsible for remarkable environmental impacts. In Europe, where about 623,000 ha are cultivated to rice, Italy represents the major rice producer with Northern Italy accounting for about 50% of European rice area. Therefore, the need for less impacting cultivation practice is prominent; consequently, research and experimentation are extremely necessary.

In this study, the traditional flooding management was compared – in terms of environmental impact – with an alternative one, characterized by an additional aeration period. This alternative water management strategy was chosen because its simplicity makes it suitable for operational contexts, and thus more likely to be adopted under real farming conditions. The comparison shows that the proposed alternative water management improves the environmental performances of rice cultivation. In detail, emissions of CH_4 decreased significantly in all the cases analysed (from 15% to 52%), with a reduction of Climate Change varying from 12% to 32%. Furthermore, in general, the alternative management applied does not affect yield, but it is effective to reduce the inorganic Arsenic content (decreases from 4 to 27%) while maintaining limited Cadmium content in rice grains.

In conclusion, alternative flooding managements including at least one aeration period can mitigate the impact on climate change related to rice cultivation, without affecting the production in terms of quantity and quality.

Since this work was carried out using data from a single growing season, in order to confirm the results the study will be repeated over the next few years, also considering different Lomellina trial sites, or other areas where flooding cultivation is commonly performed. Furthermore, future research activities should also be aimed at applying alternative water management to other rice varieties, or should evaluate the potential environmental impact, through Life Cycle Assessment approach, of other alternative water managements, such as the alternative wetting and drying. Finally, another important implementation could concern the direct measurement of methane emissions and, at the same time, of N_2O emissions.

Despite the extreme specialization of rice farmers to maximize yield, there remains limited knowledge of the beneficial effects that an alternative flooding management can lead to, by reduction of GHG emissions. For this reason, the application of LCA approach to rice cultivation can provide clear and consistent results both to encourage the adoption of mitigation strategies and for transparent and credible communication between suppliers and final consumers.

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