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Life Reptes

Renewable bio-hydrogen production technologies from lignocellulosic waste and sewage sludge co-fermentation

LIFE Project Number:	101074329
Deliverable Nº:	D4.1
Title:	Report on the national GHG emissions from rice straw management
Action:	WP4 – Task 4.1
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Date:	31/04/2023

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1. Executive summary

Massive amounts of rice straw are burned annually in the rice fields situated close to Albufera Natural Park (Spain), meaning massive emissions of greenhouse gases (GHGs) and particulate matter that affect the quality of life of surrounding populations with an important environmental impact. In Albufera, 5-6 tons of straw are produced annually in each of the 14,700-hectare cultivated. The management of this bio-waste supposes a high impact in the economy of the farmers when other techniques different of burning or burying are used. This situation is repeated yearly in other regions of Europe that are main producers of lignocellulosic crops like rice or wheat. Europe that are main producers of lignocellulosic crops like rice or wheat. Albufera park accounts for around 20% of the rice straw nationwide, being Spain the second country of rice production in the EU. Other countries at the EU level in rice production would be Italy and Greece, while countries such as Germany and France are producers of other lignocellulosic residues (LIFE21-CCM-ES-LIFE REPTES)

The surface and production of rice in Spain, according to government data for 2016, considering the largest producers, is 106,661 hectares and 134,406 tons of rice. Very close values are reported by the agricultural sectors of each region with a 10% reduction due to droughts because of climate change.

LIFE REPTES new circular model will allow the valorization of the rice straw, together with sewage sludge, by the production of renewable gas biofuels (biohydrogen and biogas) thanks to the implementation of a combination of technologies. The most innovative and the core technology of the project is the dark fermentation process (DFP) to produce biohydrogen, but the technical and economic success of the model is backed by an innovative methodology for pre-treating the rice straw prior to DFP. Furthermore, the project will demonstrate the potential of the fermented streams as co-substrate when used in anaerobic digestion in WWTPs, boosting the biogas yield by 10-43%, as it will be demonstrated in Pinedo WWTP, the biggest one of Valencia Region. (LIFE21-CCM-ES-LIFE REPTES).

LIFE REPTES will allow, not only improving the welfare of the citizens surrounding areas of lignocellulosic extensive cultivations, thus avoiding GHGs emissions and the biowaste valorisation, but also creating a new profitable and bioenergy efficient business model. (LIFE21-CCM-ES-LIFE REPTES).

GHG emissions in Spain for rice straw depend on the type of management CO_2 emission factor to incorporate only (800 Kg CO_2e /t rice straw) is greater than the burn (600 Kg CO_2e /t rice straw) at 33%. Total GHG emissions due to rice straw management in 2021 was 599,599 Kg CO_2e/year. 8 % of these emissions correspond to burning (50,620 t CO_2 e) and 92% to incorporation to the soil (548,979 t CO_2 e).

2. Purpose and scope

The objective of this study the analysis of GHG emissions from rice straw management at national level. The GHG emissions obtained through the management of rice straw at the national level will serve as a basis for comparing the reduction of GHG emissions applied to the LIFE REPTES model.

This study involves the quantification of the rice field area and rice production in each region of Spain (Andalusia, Extremadura, Catalonia and Valencian Community and Aragon) obtained from the available statistics and surveys of the relevant agricultural sectors. A review of current straw management techniques applied (burning, soil incorporation, field extraction, etc.) will direct the search for GHG emission factors related to the most employed techniques.

3. Introduction

3.1 Rice production

Rice is one of the most cultivated crops in the world. The total area where rice is cultivated is approx. 163 million hectares. 88% of this cultivated area is in Asia (Moreno-García et al., 2017). World rice production amounts to approx. 618 million tons per year (Rahimi-Ajdadi et al., 2018).

Compared to Europe, most of the rice growing areas are in the Mediterranean countries. The total European harvested area is approx. 642,000 ha and is in Italy and Spain (Moreno-García et al., 2017).

In Spain, in 2016, more than 820,000 tons of rice were produced, with 43% in Andalucía, 21% in Extremadura, 16% in Catalonia, 14% in Comunidad Valenciana and 2% in other regions (Ministerio de Agricultura, Alimentación y Environment, 2022).

The Comunidad Valenciana is responsible for around 14% of the national production of rice with a cultivated surface of 15,550 ha, mostly concentrated in the area close to the Albufera Natural Park (Sanches et al., 2014).

3.2 Rice straw

Rice cultivation produces three by-products, straw, and residues after the milling of the grains (husks and bran). Straw and bark remain almost unused, despite several studies in the past. The high mineral content is one of the main limitations for its use as animal feed, in addition to its high lignocellulose content (Vadivelo et al., 2009). On the other hand, the incorporation of rice straw to floodable soils can cause physiological damage to the crop (Dobermann and Fairhurst, 2000; Olk et al., 2000). For these reasons, rice straw often burns, emitting CO_2 into the atmosphere. Burning of rice straw in open fields results in air pollution and the release of particulate matter into the atmosphere (Abraham et al., 2016).

In Spain, a detailed evaluation of rice biomass yield, straw partitioning and harvesting was carried out. Straw yield, biomass partition indices, and fibre composition varied significantly by rice variety. The straw/grain ratio and the harvest index were on average 1.00 and 0.50 for the coarse grain and 1.25 and 0.41 for the husked grain. Biomass partition indices were significantly correlated with grain yield. (Javier Matias et al., 2019).

The amount of GHG emissions per kg of straw was obtained by considering a total of 8000 kg of rice straw for each hectare of paddy field (Gallardo et al., 2021).

3.3 Atmospheric emissions

Currently, one of the main global issues is how to reduce greenhouse gas (GHG) emissions to mitigate climate change and ensure sustainable economic growth. The EU is trying to find cost-effective ways to make the European economy more climate friendly. For example, the conversion of crop residues can represent two vital aspects for sustainable development (Abraham et al., 2016).

Rice plantations contribute to global warming of the atmosphere through methane (CH_4) emissions. Among agricultural sources, rice fields annually release between 60 and 100 million tons of methane (CH_4) worldwide, which represents 5 to 20% of total anthropogenic emissions of CH_4 (Aulakh et al., 2000; IPCC, 2006). C

Considering that the global distribution of the warming potential of CH_4 is 21 times greater than that of carbon dioxide (CO_2) (IPCC, 2006), rice fields can contribute to the global warming of the atmosphere. In addition, it can be expected that the rice fields will continue to be one of the main sources of CH4 in the future, due to the need to feed the growing human population and, as a result, there will be a need to increase the productivity of the rice production and its area sowed. (Minamikawa et al., 2006). This is especially relevant in the countries of South Asia, where rice cultivation represents a large surface, and in specific localized production regions such as Spain, Italy, or North America. Therefore, there is a great need for economically viable and environmentally sustainable ways of growing rice, which implies improving water and straw management practices and reducing CH_4 emissions. (Sanchis et al., 2012).

In Spain, emissions from agriculture represented 11.1% of total greenhouse gas emissions in 2012 (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2014), being the second most important sector after the energy sector in in terms of global emissions counted as CO_2e. (Sanchis et al., 2014).

In Spain, agriculture is the most significant activity producing CH_4 and N_2O emissions, being responsible, in 2012, for almost 50% of CH_4 emissions and 84% of N_2O (Ministry of Agriculture, Food and Environment, 2014).

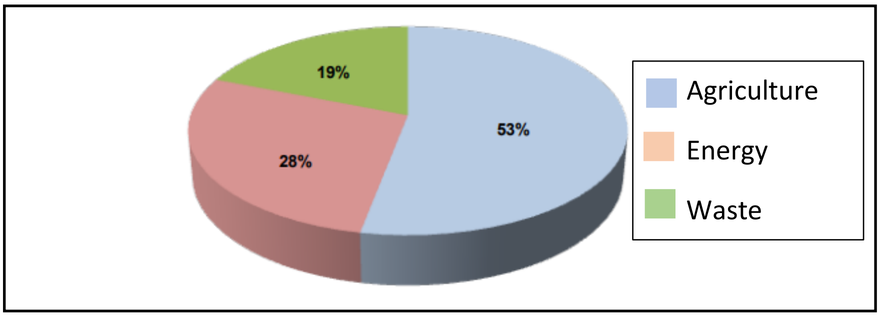

Figure 1. Anthropogenic methane emissions by sectors in the year of 2010. *Source: Yusuf et al. (2012)*

Worldwide, rice cultivation annually releases around 60-100 million tons of CH_4, contributing to global warming of the atmosphere. This suggests that around 5-19% of anthropogenic CH_4 emissions are due to rice cultivation (Aulakh et al., 2000; IPCC, 2006; Yusuf et al., 2012). Figure 2 shows the distribution of anthropogenic CH_4 emissions according to the source for the year 2010 (Yusuf et al., 2012)

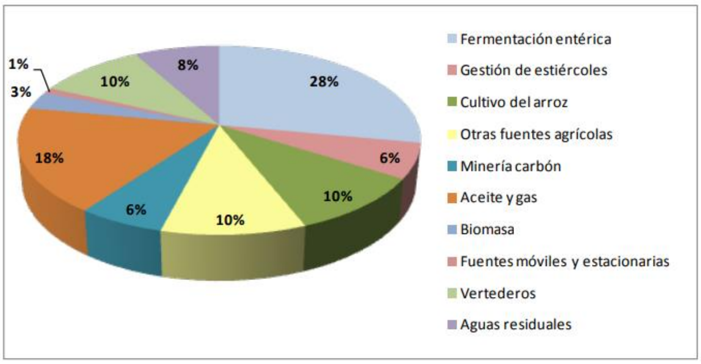

Figure 2. Anthropogenic methane emissions by emission source in the year 2010. *Source: Yusuf et al. (2012)*

Considering only anthropogenic emissions from the agricultural sector, rice cultivation is the second source after animal enteric fermentation, as shown in Figure 3. (Sanchis et al., 2014).

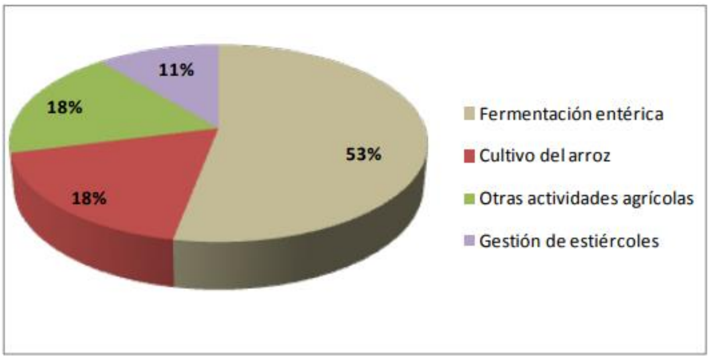

Figure 3. Anthropogenic methane emissions in the agricultural sector in 2010. ***Source: Yusuf et al. (2012)***

Since rice originally grew on naturally flooded soils, the associated CH_4 emission could be considered a natural emission source. However, the increase in production, the intensification of cultivation and artificial irrigation have led to these emissions being considered as an anthropogenic source, and as such, they must be included in the National Emissions Inventories.

In Spain, emissions in 2012 were around 300,000 tons of CO_2e. These emissions have not suffered great variations since 1990, except in years of great drought in which emissions were lower (Ministry of Agriculture, Food and Environment, 2014).

Variations in emissions are more pronounced when organic substrates are added to soils with low organic matter content (Sanchis et al., 2012). Based on the easily mineralizable carbon content, rice straw or green manures produce more CH_4 per unit of carbon than humified substrates such as compost (Neue, 1997).

3.3.1 Rice straw management alternatives

Regarding mitigation strategies for rice straw management, the recommended practices are rice straw composting, straw burning under controlled conditions, rice straw harvesting for biochar production, power generation, to be used as a substrate, or to obtain other by-products with added value. (Sanchis et al., 2012)

Therefore, future studies should focus on the search for techniques that allow the reuse of rice straw to try to obtain an environmental benefit. In this sense, Zhang et al. (2002) used it as a substrate for mushroom production. Likewise, technologies could be sought that allow the transformation of rice straw into other by-products with added value. In this way, the straw could be used to obtain xylitol (Mayerhoff et al., 1997), sugars (Karimi et al., 2006), cellulose pulp and lignin (Rodríguez et al., 2008) or enzymes such as laccase. (Niladevi et al., 2007). Another type of technology could be focused on the production of natural fibers (Reddy and Yang, 2006) or biopolymers, both combined with polyvinyl chloride (Kamel, 2004) and polypropylene (Grozdanov et al., 2006). Yang et al. (2003) used it as a construction material with insulating properties. Another solution to avoid burning straw in the field with the consequent release of polluting gases could be power generation (Zhang and Zhang, 1999; Okasha, 2007).

In recent years, a wide variety of technologies have been developed, ranging from direct burning to pyrolysis techniques to transform rice straw into more versatile energy sources (Pütün et al., 2004). Through these techniques, different by-products can be produced, such as biochar, whose characteristics can improve soil properties, avoid CH_4 emissions and sequester carbon in rice paddy soils (Zhang et al., 2010; Haefele et al., 2011; Liu et al., 2011).

3.3.1.1 Rice straw burning

The burning of rice straw can emit considerable amounts of air pollutants. Carbon dioxide was the main gas produced during combustion with emission values that oscillated between 692 g CO_2 kg dry straw 1 (10 % humidity) and 835 g CO_2 kg dry straw 1 (20 % humidity). The higher CO_2 emission values at higher moisture content in the straw can be attributed to incomplete combustion. According to the results, rice straw burning should be done after the straw has dried and under minimal humidity conditions to reduce the emission of pollutants (Sanchis et al., 2014).

Rice cultivation covers large areas of Southeast Asian countries (China, India, Thailand, and the Philippines) and localized regions of Spain, Italy, and North America. Burning of fields after harvest is still a frequent practice to remove straw cereals in many of these countries (Gadde et al., 2009).

Burning rice straw brings benefits to the farmer as it controls weeds and reduces crop diseases, prepares the field for the next harvest and releases nutrients for the next harvest (Cheng et al., 2009; Gadde et al., 2009; Lemieux et al., 2004). However, burning rice straw can contribute to harmful local air pollution, causing serious impacts on human health.

The burning of rice straw can emit considerable amounts of air pollutants, carbon dioxide (CO_2) and particulate matter (PM). Other pollutants are also emitted during the burning of rice straw crop are carbon monoxide (CO), methane (CH_4), nitrogen oxides (NOx), sulphur oxides (SOx), non-methane hydrocarbons (NMHC), and some organic and inorganic compounds, such as heavy metals, ions, volatile organic compounds (VOCs), dioxins (polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F)), and polycyclic aromatic hydrocarbons (PAHs), which are emitted in the gas phase or as constituents of particulate matter (Cheng et al., 2009, Gadde et al., 2009, Hays et al., 2005, Lemieux et al., 2004; Zhang et al., 2008). Although some of these air pollutants, such as PAHs or PCDD/F, are released in low concentrations, they have harmful toxicological properties (Lemieux et al., 2004). The emissions of these pollutants produced during the burning of rice straw can lead to local pollution problems and impacts on human health (Gullett and Touati, 2003; Hays et al., 2005; Lin et al., 2007), such as example, asthma (Torigoe et al., 2000). Furthermore, some of these contaminants have toxicological properties and are considered potential carcinogens (Gadde et al., 2009).

For these reasons, the burning of rice straw has been regulated and restricted in some countries despite its economic and practical benefits. However, it continues to be the most frequent practice in many other countries around the world. The European Union regulated a few years ago the agri-environmental aid of the Community Agricultural Policy (PAC) in relation to the cultivation of rice.

3.3.1.2 Rice straw incorporated into the soil

Sanchis et al., 2012 reviews the state of the art of factors affecting CH_4 emissions in rice fields, with a focus on organic soil matter content and water management practices. Methane emissions from rice fields can be as much as 90% higher in continuously flooded rice fields compared to other water management practices, independent of straw addition. Water management systems that involve partial or complete absence of flooding during the growing season, such as mid-season drainage, intermittent flooding, and seepage control, can reduce CH_4 emissions.

The amount of straw applied, and continuous flooding and water management have a strong influence on CH_4 emissions (Yan et al., 2009). However, knowledge about the effect of the type of organic matter, on the rate and quality of rice straw, on CH_4 emissions from rice fields is still limited.

CH_4 emission from paddy fields results from a complex process where organic matter in the soil is anaerobically decomposed and eventually CH_4 is produced as a by-product in the metabolism of methanogenic archaea. Anaerobic conditions result from the flooding of fields, which reduces the availability of oxygen in the soil (Conrad, 1993; Neue, 1997; Watanabe et al., 2001).

Regarding the organic matter content of the soil, the easily degradable organic matter in the soil also constitutes an important source for the formation of CH_4 in rice fields (Neue et al., 1995). Therefore, the addition of organic matter such as rice straw to a flooded rice field provides an additional source of carbon, which can serve as a substrate for methanogenic activity (Wassmann et al., 1993b).

3.3.1.3 Comparison of straw management alternatives

Sanchis at al., 2014 calculates the seasonal emission of CH_4 by averaging the accumulated emission throughout the entire crop cycle for different straw management alternatives as burning, soil incorporation, straw removed from the field and mulching with and without flooding (Table 1). The alternative in which straw was incorporated into the soil showed the highest CH_4 emission value (557.5 kg CH4/ha), being statistically different from any of the other alternatives. The alternatives consisting of application of straw on the surface as a cover, with and without water, gave average value of 401.9 kg CH_4/ha and 371.5 kg CH_4/ha, respectively. The cases in which lower emissions were obtained were when the straw was burned (319.2 kg CH_4/ha) and, logically, when it was removed from the field (249.9 kg CH_4/ha) (*Sanchis at al., 2014*).

Table 1. Average of the emissions accumulated in different vegetative periods and stationary emissions of CH_4 (Kg/ha)

Alternativa	Vegetativa (kg CH_4/ha)	Reproductiva (kg CH_4/ha)	Maduración (kg CH_4/ha)	Emisión estacional (kg CH_4/ha)	
				Promedio	desviación estándar
1. Paja retirada	58,3^{a}	104,2^{a}	87,4^{a}	249,9^{a}	12,1
2. Paja quemada	57,6^{a}	140,1^{ab}	121,5^{a}	319,2^{b}	34,8
3. Paja incorporada	89,0^{c}	252,3^{c}	216,2^{c}	557,5^{d}	41,9
4. Paja superficie (cubierta)	64,4^{ab}	176,2^{b}	161,3^{b}	401,9^{c}	21,5
5. Paja superficie (sin agua)	78,9^{b}	163,2^{ab}	129,4^{ab}	371,5^{bc}	44,8

^{a,b,c}: Valores que difieren estadísticamente a probabilidad ≤ 0,05. Comparación entre filas

Source: Sanchis et al, 2014

In some rice production areas, competent bodies recommend keeping the rice straw in the fields to mix it with the mud and use it as a source of organic fertiliser for the soil while avoiding the generation of gases generated during straw burning despite this technique generates an increase in methane emissions.

Flooding and drainage of rice fields is one of the most principal factors in controlling CH_4 production and fluxes. CH_4 emissions vary depending on the water management conducted in the rice fields, being higher in fields that remain flooded during the rice growth period, than in those that are flooded intermittently (Sass et al., 1992; Husin et al. al., 1995; Yagi et al., 1996). In numerous studies it has been observed that by draining the fields a significant reduction in CH_4 emissions is produced. A simple drainage in the middle of the productive period can reduce emissions per cycle by over 50% (Yagi and Minami, 1990; Kimura et al., 1991; Kimura et al., 1992; Sass et al., 1992; Yagi et al., 1997).

In the Valencian Community, there was a straw management plan for 2022 that was drawn up as a continuation of the one that has been developed during the period 2018-2021, where several measures were implemented aimed at minimising the impact of straw management, as well as managing this agricultural residue in such a way that it does not generate negative impacts on the natural environment, encouraging practices that increase reuse, both by incorporating it into the land and by collecting the straw and using it as a raw material in other processes (food, agriculture, etc.) as a raw material in other processes (animal feed, use as compost, etc.), with the collaboration of the agricultural sector.

Sanchis et al. (2014) studied the emissions produced during the combustion of straw obtained from a rice field in the Albufera Natural Park. The results are reproduced below for the three straw moisture levels (5%, 10% and 20%) (Table 2).

Table 2. CO_2 emissions measured during the burning process with different humidity levels (%)

Grado de humedad (%)	CO_2 (g CO_2/kg MS quemada efectiva)	
	Promedio	desviación estándar
5	776	21
10	692	28
20	835	136

Source: Sanchis et al, 2014

According to the study by Sanchis at al. the presented results did not show significant differences between different straw moisture contents. However, to carry out the carbon balance, the result corresponding to 10% straw moisture was selected, as it is considered the most representative of the conditions that occur in rice paddies during the burning season.

The emissions produced between the different straw management alternatives were expressed in CO_2 equivalents and it was considered that the burned straw applied at a rate of 8 t/ha. In this way, the results obtained were as follows:

Table 3. Equivalent CO_2 emissions of different management alternatives for the studied straw

Alternativa	Emisiones durante el cultivo (kg CO_2-eq/ha)	Emisiones durante la quema (kg CO_2-eq/ha)	Emisiones totales (kg CO_2-eq/ha)
1. Paja retirada	5.248		5.248
2. Paja quemada	6.703	3.253	9.956
3. Paja incorporada	11.708		11.708
4. Paja superficie (cubierta)	8.440		8.440
5. Paja superficie (sin agua)	7.802		7.802

Source: Sanchis et al, 2014

Based on these values, the highest emissions are produced in the alternative of incorporated straw, that is, when puddling is conducted. These emissions were 18% higher than those produced in the alternative in which rice straw is burned. However, it should be noted that during the burning process, other pollutants without direct equivalence with CO_2 are also emitted, such as particles, dioxins, PCBs, metals, etc. that are not accounted for in this balance sheet. Similarly, potential emissions associated with alternative uses of straw, such as aerobic decomposition or burning for energy purposes, were not considered. The straw alternatives on the surface produced lower CO_2e emissions than the two previous alternatives. The lowest emissions occurred in the alternative in which the straw was removed from the field. Therefore, from the previous results, both the alternative of incorporating straw and that of burning represent the highest emissions, which is why they are not considered a good alternative for the management of rice straw (Sanchis et al, 2014).

The highest CH_4 emissions occurred in the incorporated straw alternative, with a seasonal emission of 557.5 kg CH_4/ha. From the point of view of air pollution, regarding CH_4, the alternative of straw incorporated into the field was the most unfavourable. After adding the CO_2 emissions produced during the cultivation cycle and the burning of the straw (if applicable), the highest CO_2e emissions occurred in the alternative of incorporated straw, being 18% higher than those emitted in the alternative in which the straw is burned. The alternative that produced the lowest greenhouse gas emissions was the removal of straw. However, it is proposed to include in future studies the emissions generated by the machinery used, considering the economic and energy costs that each of them entails (Sanchis et al., 2014).

4. Methodology

A methodology was designed to gather the information about national surface and rice production in Spain and the main techniques used of rice straw management/disposal.

We gathered the information from four main sources:

- The statistics of the Ministry of Agriculture, Fisheries and Food of Spain (www.mapa.gob).

- The information from the main rice producing regions in Spain (Andalucía, Extremadura, Catalunya and the Comunidad Valenciana). Surface data and rice production were obtained from the government website, and direct request of information and consultations to experts in the official regional agencies in charge of this type of information. Technical consultations were carried out regarding the type of management of straw currently applied (burning, incorporation into the soil, etc.) and the percentage of application of each of them.

- We also made consultation to experts from universities, association of rice growers, regional agricultural sectors, specialists in rice production, etc.

- Review of technical articles regarding rice straw, rice straw management techniques and relevant emission factors for GHG of main straw management techniques. Information for assessing GHG emission factors during the cycle of rice production (sowing, production, and disposal of rice straw) was obtained from in scientific articles for local conditions. List of articles reviewed is shown in the references section. Table 4 shows the list of regional agencies contacted.

Table 4. Regional agencies contacted from information about rice producing, area and management of rice straw

Region	Regional agency	Number of contacts	Result
Comunidad Valenciana	Conselleria de Agricultura da Comunidad Valenciana	4	General information about rice straw: Instituto de Ciencia y Tecnología Animal – UPV
Andalucía	Junta de Andalucía	5	General information on rice production: Consejería de Agricultura, Pesca, Agua y Desarrollo Rural www.juntadeandalucia.es
Extremadura	Junta de Extremadura	7	General information on rice production: Servicio de Sanidad Vegetal Dirección General de Agricultura y Ganadería Consejería de Agricultura Desarrollo Rural, Población y Territorio
Cataluña	Instituto de Investigación y Tecnología Agroalimentaria	5	General information on rice production: Secretària del Gabinet Tècnic Departament d'Acció Climàtica, Alimentació i Agenda Rural
Aragón	Sección de Análisis, Panificación Y Seguimiento Agrario	10	General information on rice production: Sección de Análisis, Planificación y Seguimiento Agrario

5. Results

5.1 Data from official national statistics

Through the website of the Ministry of Agriculture, Fisheries and Food of Spain (https://www.mapa.gob.es/es/agricultura/temas/producciones-agricolas) the following values were obtained as reference year 2016.

Figure 4 shows rice production area in main production aeras in Spain and their relative relevance on the total national area. Main production areas are Andalucía with 37% and Extremadura with 23% totaling more than 60% of the rice production area.

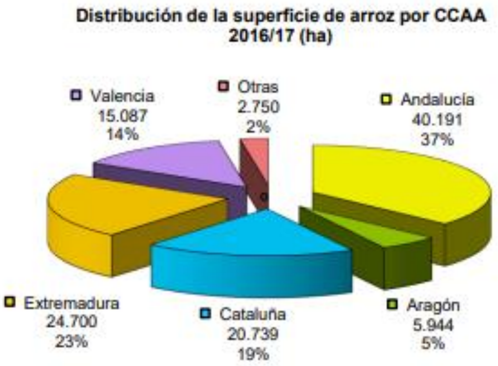

Figure 4. Percentage distribution of surface dedicated to rice cultivation in the main production areas in Spain by Autonomous Regions Source: Prepared by SGCHI based on data from the S.G.T. (Advances of areas and productions July 2016).

Figure 5 shows that the percentage distribution of rice production in Spain. Main production areas in Spain are Andalucía (43% of total production) and Extremadura (21%).

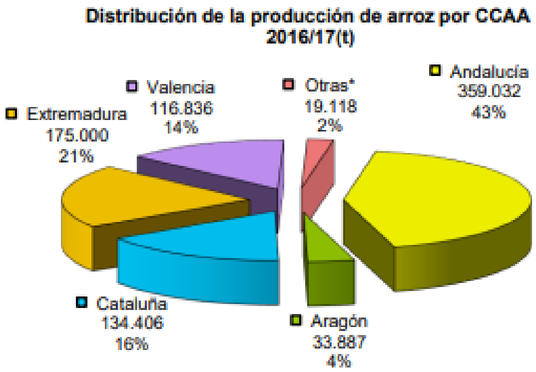

Figure 5. Distribution percent and mass of rice production in Spain by Autonomous Communities Source: Prepared by SGCHI based on data from the S.G.T. (Advances of areas and productions July 2016).

Figure 6 shows the evolution of the rice area and rice production in Spain in the period 2011-2016. It also presents the annual productivity during this period with an average value of 7.7 t/h.

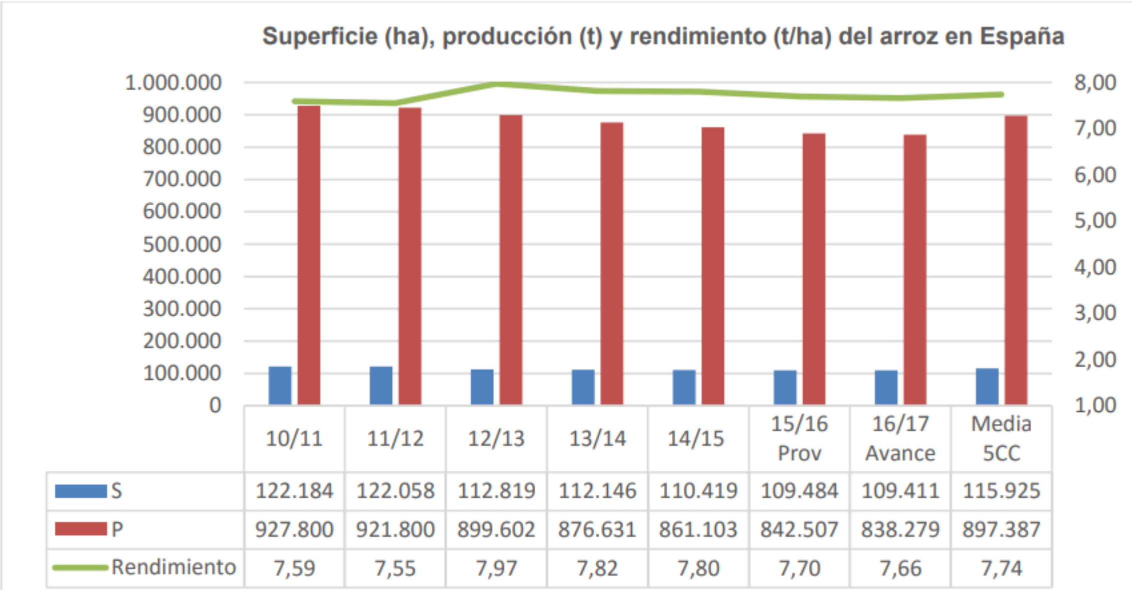

Figure 6 - Evolution of rice area and production in Spain by Autonomous Communities Source: Prepared by SGCHI based on data from the S.G.T. (Advances of areas and productions July 2016).

5.2 Data from regional agencies

5.2.1 Rice production, surface, and management

Table 5 shows the information received from the regional agencies related to rice surface and production by region corresponding to the year 2021. These number are compared with those published by the Spanish Ministry of Agriculture corresponding to the year 2016.

Table 5. Information of Government and Agricultural Agencies data on rice surface and production

Information	Government (2016)		Agricultural agencies (2021)		
Production areas	**Surface (hectares)**	**Productivities (tons)**	**Surface (hectares)**	**Productivities (tons)**	**Contact**
Comunidad Valenciana	15,087	116,839	14,182*	108,660*	Conselleria de Agricultura da Comunidad Valenciana
Andalucía	40,191	359,032	37,921	331,830	Junta de Andalucía
Extremadura	24,700	175,000	23,218*	162,750*	Junta de Extremadura
Cataluña	20,739	134,406	20,979	134,406	Instituto de Investigación y Tecnología Agroalimentaria
Aragón	5,944	33,887	3,926	242,17	Sección de Análisis, Panificación y Seguimiento Agrario

*Unreported values are calculated considering the factor government data versus data reported from agriculture agencies of 2021.

In Table 6 shows the types of management of rice straw in each region, based on the information received from the regional agricultural agencies. According to Law 7/2022 (8/04/22) and Resolution (17/05/22) of the Council of Agriculture, Rural Development, Climatic Emergency and Ecological Transition of Spain, the burning of rice straw can only be carried out in some specific cases, as is the case of the Comunidad Valenciana.

Table 6. Information of Agricultural Agencies on the types of management of rice straw (2021)

Production areas	Burning (%)	Incorporation to the soil (%)	Animal feed (%)	Other (%)	Total (%)
Comunidad Valenciana	68	7	no information	25	100
Andalucía	0	**100**	0	0	100
Extremadura	no information	no information	no information	no information	no information
Cataluña	4.3	94	1.7	0	100
Aragón	0	**100**	0	0	100

5.3 GHG emission factor for straw management techniques

In this study we have calculated the emission factors calculated for the different rice straw management techniques

Net CO_2 e emissions (Kg CO_2 e/hectare of rice production) corresponding to the management of the straw in both techniques are calculated as difference between the global CO_2e emissions during the cultivation period in both cases and the global during the cultivation period considering rice straw is withdraw from the field. These data were taken from the study made by *Sanchis at al., 2014*. Using these net CO_2e emissions, CO_2e emission factors (as t CO_2e*/ha of rice straw*) for two type of straw management techniques were calculated considering a yield of rice straw of 8 t straw/ha (*Gallardo et al, 2021*).

Table 7 shows the calculated CO_2e emission factors for two type of straw management techniques: burning and incorporation to soil.

Table 7. CO_2e emission factors of rice straw management

Rice straw management	CO_2e emission during all rice cultivation period		Emission factor
	Kg CO_2e/hectare	Kg CO_2e /t rice straw	Kg CO_2e /t rice straw
Withdrawn	5,248	656.0	
Burning	9,956	1,244.5	600
Incorporation to the soil	11,708	1,463.5	800

According to the table above, the emission generated by incorporating rice straw into the soil is 33% higher than the emission generated by burning rice straw.

5.4 Spain GHG emissions

Total straw production in each productive region is calculated by multiplying the rice surface in 2021 in each region (information obtained from Agricultural Agencies) by the straw yield (8 t/ha)

Table 8. Rice straw production in Spain.

Production areas	Surface (hectares)	Straw production (t)
Comunidad Valenciana	14,182*	113,456
Andalucía	37,921	303,368
Extremadura	23,218*	185,744
Cataluña	20,979	167,832
Aragón	3,926	31,408
Spain (Total)	**100,226**	**801,808**

National GHG emissions due to the management of rice straw in each region is calculated by multiplying the quantity of straw managed by each technique (incorporation into the soil or burning) by the corresponding emission factor (Table 9).

Table 9. Calculation of emissions considering the factors of burning and incorporation into the soil

Region	Quantity of straw (t/year)			CO_2e emissions (t CO_2e/year)
	Burning	Incorporation to the soil	Other	
Comunidad Valenciana	77,150	7,942	28,364	52,644
Andalucía		303,368		242,694
Extremadura		185,744 *		148,595
Cataluña	7,217	157,762	2,853	130,540
Aragón		31,408		25,126
Spain (Total)	84,367	686,224	31,217	**599,599**

*Unreported management of rice straw

Total GHG emissions in Spain due to rice straw management in 2021 was 599,599 t CO_2e/year. 8 % of these emissions correspond to burning (50,620 t CO_2 e) and 92% to incorporation to the soil (548,979 t CO_2 e).

6. Conclusions

Total surface dedicated to rice cultivation was 100,226 ha. Considering a straw yield of 8t/ha, total production of straw in Spain in 2021 was 801,808 t/year

In Spain there are three main alternatives for the management of rice straw: incorporation to the soil (80 %), burning (14,5 %) and withdraw for other uses (5,5%).

Ley 7/2022 (04/08/22) and Resolution of 17/05/22 by the Minister of Agriculture, Rural Development, Climatic Emergency and Ecological Transition of Spain prohibits the burning of plant residues. The burning of plant residues generated in the agricultural or forestry environment may only be permitted when authorised by the competent body of the Autonomous Communities, either for phytosanitary reasons or with the aim of preventing fires. There is a temporal and partial authorization of burning of rice straw in the case of the Valencian Community, Albufera, which is located REPTES project.

The GHG emission for rice straw incorporated to soil (800 kgCO_2e /t rice straw) is a 33% higher than for the burning of rice straw (600 kgCO2e /t rice straw).

Total GHG emissions in Spain due to rice straw management in 2021 was 599,599 t CO_2e/year. 8 % of these emissions correspond to burning (50,620 t CO_2 e) and 92% to incorporation to the soil (548,979 t CO_2 e).

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This project received funding from LIFE programme under grant agreement Nº 101074329.