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Rice Straw: A Waste with a Remarkable Green Energy Potential

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Abstract: With reference to the province of Novara in northwest Italy, this study aims to raise awareness about the environmental benefits that can derive from the use of alternative rice straw management practices to those currently in use, also highlighting how the use of these straws for energy purposes can be a valid alternative to the use of non-renewable resources. Using the LCA (Life Cycle Assessment) method, the two rice straw management practices currently in place (open field combustion and straw incorporation) were compared with an alternative strategy consisting in their collection and removal. The results show that removal of straw allows reducing the emissions of pollutants significantly: about one-hundredth of the PM (Particulate Matter) formation compared to the open-field burning and about one-tenth of the ozone depletion (CFCs, HCFCs, halons, etc.) compared to both the other two practices. Moreover, the LCA results show how the use of rice straw to produce energy as an alternative to conventional fuels helps to reduce the global warming potential of rice cultivation.

Keywords: rice straw; vegetable waste management; climate change reduction; green renewable energy

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1. Introduction

In the last decades, the international community has made considerable efforts to reconcile the increase in air pollution, with evident repercussions on both human and planet health [1,2], with the growing global demand for energy.

For this reason, in the most disparate sectors, a consistent effort has been made in order to develop alternative solutions which, due to their innovative character, their higher efficiency or their lower environmental impact, were more sustainable than traditional ones [3–8].

Despite this, the 7th Sustainable Development Goal of the 2030 Agenda for Sustainable Development [9], which aims to guarantee sustainable energy, is far from being achieved [10]. Whatever the energy transition pathway is considered [11–13], by 2050, renewable energy sources (solar, wind and biomass) [14] should play a leading role.

Based on these considerations, it is also important to understand to what extent renewable energy sources are an advantage, both for the environment and for the economy, in relation to the place where they are available [15,16], classifying their sustainability with respect to the traditional ones that however will be used.

The province of Novara, the object of this study, shows a clear agricultural aptitude that involves a great production of biomass. During 2020, about 44% of the province area was dedicated to agricultural production, of which approximately 60% was used for rice cultivation [17].

The disposal of the rice straw that is produced partly takes place in open field burning. This practice, also widespread in others countries [15,18–20], is still in force even if the European legislation [21] classifies this agricultural residue as a plant-tissue waste (European Waste Code EWC 02.01.03) as it does not have reuse.

In the province of Novara, this practice, together with the emissions of sulfur dioxide (SO_2), NO_x and Volatile Organic Compounds (VOC) from other sources (vehicular traffic and heating), must be considered one of the main causes of the production of particulate matter (PM).

Considering the negative effects on human health [22], the local government pays specific attention to PM emissions, and the European community has activated actions aimed at regulating the improvement of the state of the environment [23] by introducing, among the other preventive actions, the well-known "polluter-pays principle" [24].

In the Piedmont Region, where the province of Novara is placed, the agricultural sector contributes 14% [25] of the total to air pollution (200 tons/y of PM10 and 190 tons/y of PM2.5). The geographical context, coupled with the prevailing direction of the winds, gives rise to the stagnation of atmospheric pollutants since the mountain ranges act as a barrier [26–28].

The aim of this study, with reference to Novara, is to evaluate how much a change in the method used for the disposal of the rice straw can produce a positive impact in relation to the environment. The environmental performance of these disposals was evaluated and compared in terms of Global Warming Potential (GWP), Particulate Matter (PM), Fossil Resource Scarcity (FRS), Ozone Depletion (OD) and Terrestrial Acidification (TA).

In the Novara province, as in the rest of the world [29,30], the development of adequate policies of economic and fiscal incentives or sanctions may be necessary to promote changes to achieve more sustainable anthropogenic activities. At the same time, an improvement in the traditional agriculture practices and energy production methods may be necessary to integrate them into a circular system [31]. In order to assess whether the proposed changes have a positive fall-out, their effects must be critically studied and evaluated.

For the following analysis, the Life Cycle Assessment (LCA) approach was used because it is widely consolidated [32] and useful for quantifying the potential impacts on the environment and human health with reference to reliable databases. OpenLCA 1.10.3 (©GreenDelta 2020) has allowed inserting input/output data evaluated directly according to the IPCC guidelines [33–35].

In a recent research [36], an in-depth analysis of LCA models for optimal waste management was proposed, comparing the inventory and impact assessment databases used in these models, as well as the fall-out of various technical assumptions available. Among the useful results, the analyses suggest that the use of specialized LCA models should be preferred over the generic LCA.

A similar approach was adopted for rice straw management using the LCA software combined with specialized databases. The reference inventory database used is Agribalyse®_v3.0.1_27052021, and the method referred to for the impact assessment is ReCiPe 2016 Endpoint (E); moreover, for the normalization World (2010), E/A was used.

In this paper, a new practice, which involves the collection and baling of rice straw (CB), was compared with the well-established practices of open field burning (OFB) and soil incorporation (SI).

Since the collection and baling of rice straw is intended for subsequent use of this biomass for energy production, in the analysis of the other two processes, a burden was applied. This burden, as explained below, was assessed considering that since in the case of OFB and SI, the straws are not used to produce energy, the energy supply will take place using traditional energy sources.

Although in-depth research was carried out on LCA applied to straw management, there are few studies that, for this specific area, consider savings on the energy portfolio as one of the benefits of using this new renewable resource. This work will generate new information on energy harvesting in an area with a growing demand for energy and with a high level of air pollution, such as the province of Novara.

2. Regional Context

The province of Novara has an extension of about 134,000 hectares (less than 0.5% of the extension of Italy) and is characterized by a temperate climate with humid summer. These climatic characteristics combined with the significant presence of water allow the cultivation of various agricultural species [17], mainly rice and corn. The common type of rice cultivated in this area belongs to the "Baldo" variety, similar to the more famous Asian variety "Japonica" characterized by round, thick and hard grains. A single rice harvest season commits farmers from January to October. The cultivation carried out by submersion in water is characterized by high standards of agricultural mechanization [37] that affect every phase of the process, from the initial preparation of the soil to the harvesting.

All agricultural processes take place with medium-power tractors arranged with specific equipment, while the harvest is carried out with high-power combine harvesters. The flooding of the fields (lasting about 120 days) is performed using the water available through irrigation canals. It must be noted that in the cultivation of rice, especially in the growth phase due to the interaction of the fertilizer with the flooded soil, important quantities of CH_4 and N_2O are generated [19,38,39], and the methanogenesis occurs by bacterial action as a transformation of Soil Organic Carbon (SOC) under anaerobic conditions [40].

The cultivation of rice involves residues: harrowing produces straw, and milling produces husk and chaff. The husk (about 20% by weight of the rice grains) and chaff (about 10% by weight of the rice grains) have an economic value (price in January 2022 was about 45 EUR/ton for the husk, 170 EUR/ton for the chaff [41]) since they are moderately employed for energy, pharmaceutical and green building purposes. Rice straw (about 90% by weight of the rice crop) is almost unused in animal husbandry. Rice straw is not suitable for feeding since it has a high content of Silica (SiO_2) equal to approximately 13% by weight, and its poor absorbent characteristics make it unsuitable for use as a litter.

For this reason, the full amount of rice straw produced is commonly considered waste, and its removal from the ground is infrequent. Therefore, in the province of Novara, where about 220,000 tons of rice grains were collected in 2020 [17], an approximately equivalent amount of straw was incorporated into the soil or burned in the field.

About three-quarters of the rice straw produced in the Novara province is disposed of by soil incorporation (SI), and the rest, similarly to what is worldwide practiced, is burned in an open field (OFB). Both disposal methods generate benefits linked to the reintroduction of elementary substances into the soil (C, K, N, P and others) [42] and to the elimination of weeds from the field [43–45]. Furthermore, the ashes produced during OFB have a fertilizing effect because they mainly contain magnesium oxides (MgO) and potassium (K_2O), but also a quantity of silica (SiO_2), which depends on the kind of rice grown and increases as the height of the stem raises [46]. While these widely used disposal practices for rice straw have some agronomic benefits, as they reduce the number of artificial fertilizers and herbicides used, on the other hand, they generate negative environmental effects increasing air pollution (mainly PM and CO) and GHGs emissions (mainly CO_2, CH_4 and N_2O) [18,19,47].

3. Life Cycle Assessment (LCA) Method

The process analyzed using the LCA is that of the straw disposal (boundary system), which is independent of that of the rice cultivation (zero burden approach). For this reason, although the rice cultivation phases were described for completeness, the inflows and outflows linked to these processes were not taken into consideration for the analysis.

A comparative assessment approach was adopted in analogy to other LCA studies [20,48]. Agribalyse® was adopted as a database due to its content of fertilizers, machinery and buildings, which is a relevant feature to this study. The ReCiPe 2016 impact assessment method was used in force of its output indices, which are useful for this study (GWP, PM, FRS, OD, TA).

In carrying out the analysis, it was taken into account that the three methods of straw disposal, mentioned in the introduction paragraph as OFB, SI and CB, affect the cultivation process in different ways.

In fact, both in the case of CB and in the case of OFB, additional fertilization is necessary compared to those normally scheduled for the cultivation of rice. Moreover, it was taken into account that only in the case of straw CB an energy potential will be available to be exploited later (Table 1). For this reason, an energy deficit with its environmental burden was associated with both the OFB and SI.

Table 1. Straw Energy Potential.

Quantity	Value
Straw Collected ÷ 20% moisture (kg/ha)	3658
LHV [(1)] (MJ/kg)	14
Energy potential (GJ/ha)	51.2

[(1)] LHV is the Lower Heating Value reported in [49].

To evaluate the burden to apply, in accordance with the Italian energy supply scenario [50], only the fraction of energy produced using non-renewable sources (approximately 58% of the energy potential of rice straw, i.e., 29.6 GJ/ha) was considered.

The required masses of raw materials are shown in Figure 1.

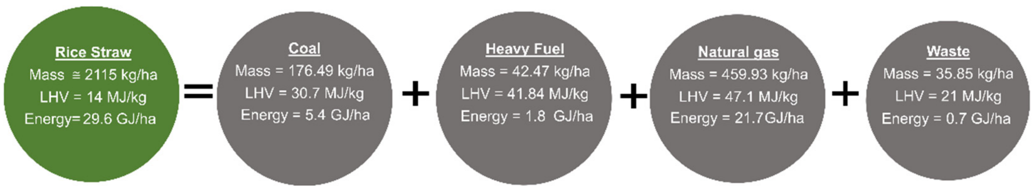

Figure 1. Equivalent energy potential using non-renewable raw materials.

In the following paragraphs, the processes studied are described, and the data used for the LCA are provided. The functional reference unit is the hectare (ha), and the inflows or outflows deemed of little relevance to the result of the analyses were highlighted and considered as cut-off elements. Furthermore, the CO_2 emissions deriving from the combustion of rice straw are not reported as it is assumed that they will be reabsorbed by the biomass during the following growing season [33]. Where present, the outflows related to the water lost by the biomass were not reported because they have no environmental impact.

The limitations of the LCA analysis carried out are the assumed standardization of agricultural practices that could be a little different from farm to farm also in relation to the type of agricultural machinery used and cut-off elements.

3.1. Cultivation Process

The rice cultivation process begins with the plowing of the field (January), which is subsequently leveled (January/February) and then fertilized (March). The processes listed above are followed by harrowing (March) to promote fertilization and aerate the soil. The field is then sown (April) and again both fertilized and weeded (June and August). The rice harvest takes place in September/October.

All the phases, reported in the Gantt (Figure 2), are mechanized with the exception of irrigation. Irrigation is carried out, based on the availability of water and the permeability of the soil, with three different methods: permanent flooding (WFL), dry seeding and flooding in the growth phase (DFL), and dry seeding and alternate wetting and drying (DIR).

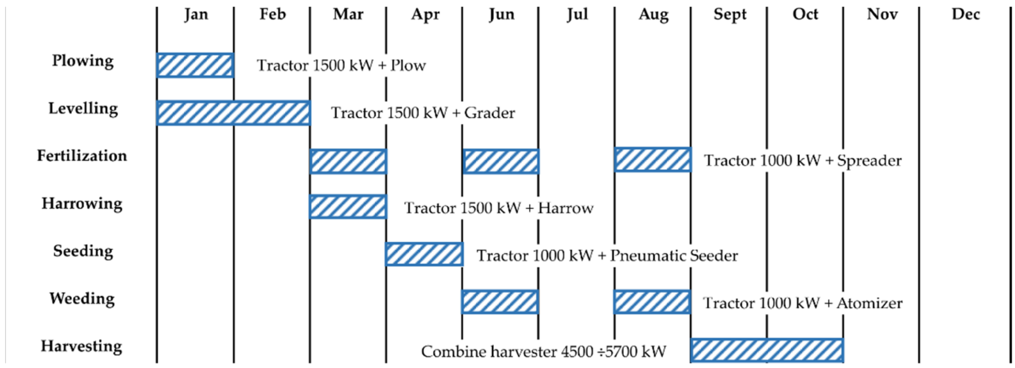

Figure 2. Gantt diagram: phases of rice cultivation and agricultural machinery used.

The water for flooding comes from a network of local canals. The flooding of the fields occurs through the opening and closing of bulkheads, positioned in the irrigation canal and manually operated, which distribute water by gravity.

In some cases, sowing takes place with a technique that involves flooding the field and then the aerial distribution of the seeds. In this case, before flooding, the field is compacted again to improve its impermeability.

The combine harvester can be configured to simply drop the straw to the ground or to shred it and spread it all over the field. This second mode increases the fuel consumption of the combine harvester by approximately 5–10%. This higher fuel consumption was considered a cut-off element in the analyses carried out.

3.2. Open-Field Burning (OFB)

Just after the harvest of the crop, the process of disposal by combustion is started. The OFB process occurs by triggering a localized fire, which is then spread throughout the field, triggering subsequent localized fires. During combustion, atmospheric pollutants (emissions to air) and ashes (emissions to soil) are produced in quantities proportional to the straw burned (Figure 3).

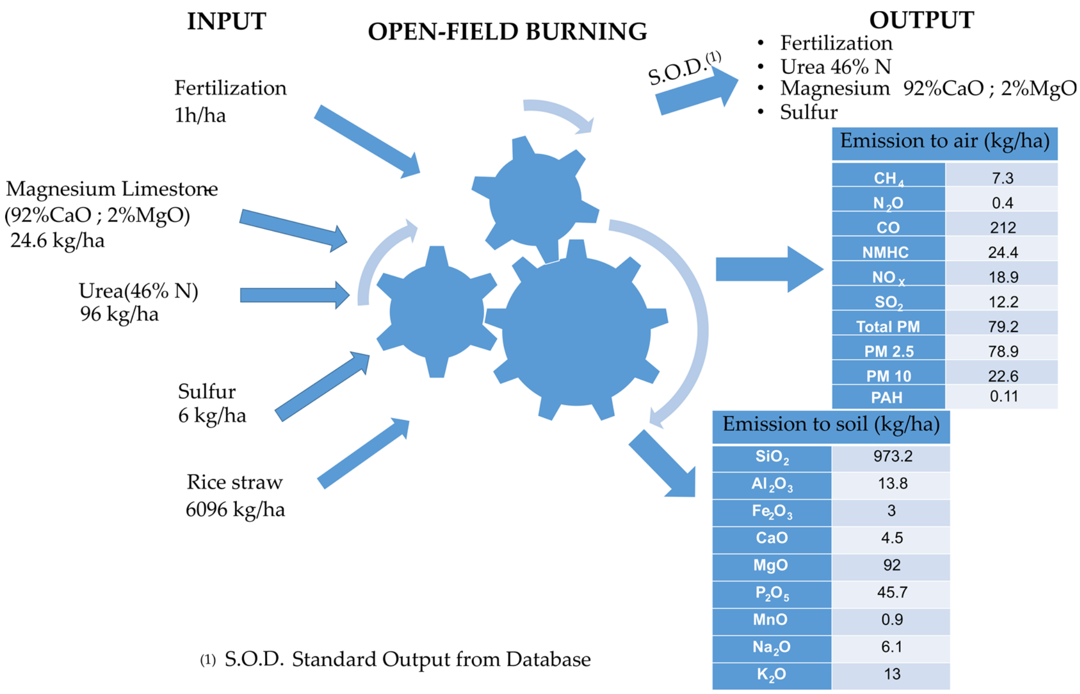

Figure 3. Inventory analysis for the open-field burning process.

The process does not require the use of agricultural machinery, and the quantities of substances used (e.g., fuel) are not relevant, so they were considered as cut-off elements of the process.

The number of above-ground residues burned was calculated in accordance with the IPCC guidelines [34], taking into account the type of rice grown. For the evaluation of emissions to air, the emission factors reported in [18] were used, which are in the range of values reported by the IPCC for the combustion of agricultural residues [35].

Regarding the ashes, their composition was evaluated on the basis of [51]. The incorporation of the burned straw was not considered in the data inventory analysis because it is carried out during the winter plowing of the soil (January), which is an operation that is anyway part of the rice cultivation process.

Moreover, compared to the rice cultivation process, the OFB requires additional fertilization [52], which is carried out by means of a spreader pulled by a medium power tractor. All the numerical values used for the data inventory are shown in Figure 3, while the data for the calculation of the burden relating to the lack of energy production are shown in Figure 1.

3.3. Straw Incorporation (SI)

About a month after harvesting and straw production, the field must be harrowed to incorporate the chopped straw. The operation is performed by means of a harrow towed by a medium power tractor. In the period between harvesting and SI, the mass of the rice straw is reduced due to both the decrease in water content and the aerobic decomposition of its cellulosic fraction. Following the de-polymerization of cellulose in the aerobic decomposition process, glucose is formed, which oxidizing generates CO_2 and H_2O that are emitted from the biomass. These two products were considered as cut-off elements.

The remaining quantity of straw per hectare of land was determined using the following Equation (1) as proposed in [53]:

$$y(t) = y_\infty + (y_0 - y_\infty) \cdot e^{-k \cdot t}, \tag{1}$$

where $y(t)$ is the specific mass (kg/ha) remaining after a time t (months), y_∞ is the specific mass (kg/ha) remaining after the end of the decomposition process, y_0 is the initial specific mass (kg/ha) and k is the rate at which decomposition takes place (months^{-1}). Table 2 shows the values of the coefficients in Equation (1) useful to describe the rice straw incorporation in the Novara province.

Table 2. Numerical values of the coefficients reported in Equation (1).

Coefficient	Numerical Value
y_∞	1829 kg/ha
y_0	6096 kg/ha
k	0.596 months^{-1}

Using Equation (1), the reduction in weight of the biomass is about 30% after one month from the harvest, and the quantity of residual straw to be incorporated is 4180 kg.

Figure 4 shows the flows for the Data Inventory Analysis. The emissions of CH_4 and N_2O reported in this figure were calculated using the equations proposed in [33,34], taking into account the reduction in the mass of the straw following the decomposition. The data for calculating the burden due to the lack of energy production in this process are shown in Figure 1.

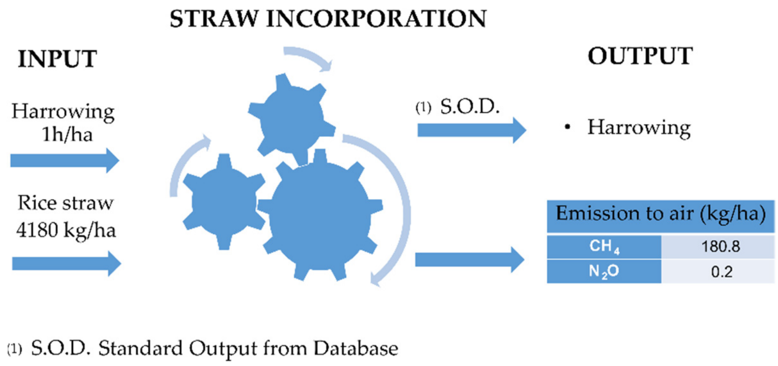

Figure 4. Inventory analysis for rice straw incorporation.

3.4. Rice Straw Collection and Baling (CB)

The rice straw is removed when the moisture content has dropped from 50% (typical value for biomass just after harvesting) to about 20% since a low moisture content prevents the activation of harmful fermentation processes. The straw, baled in a cylindrical or polygonal shape, is wrapped in a nylon film, loaded onto a trailer and transferred to the storage area inside the farm. Figure 5 reports the additional fertilization operation [52] and the energy content of the baled straw.

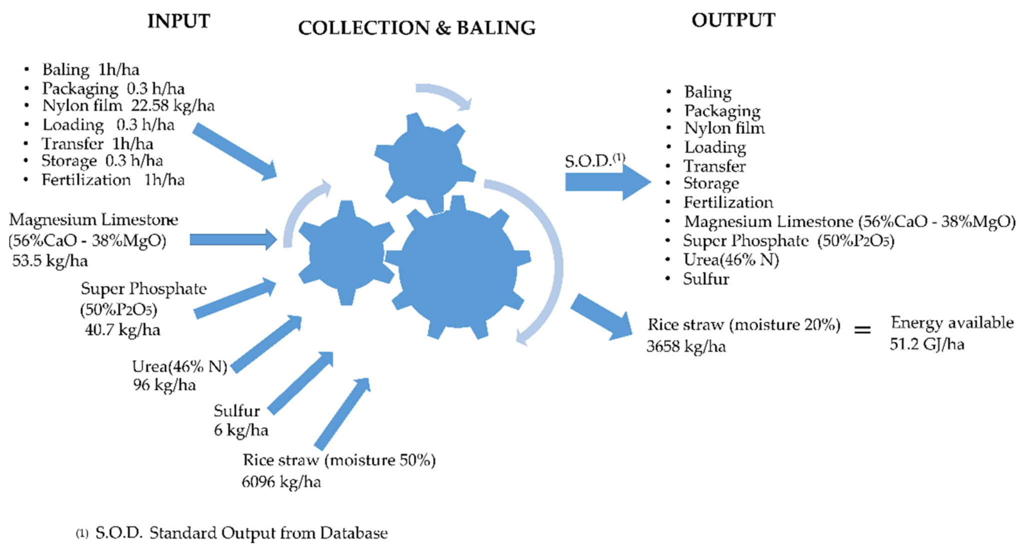

Figure 5. Inventory analysis for the collection and baling.

4. Results and Discussion

Using the LCA analysis, it was possible to evaluate the sustainability of each rice straw disposal management in order to choose the best strategy with regard to the environment. Furthermore, the current study shows how many fossil resources are actually used to produce an energy equivalent to that available in the rice straw.

The analysis is performed by comparing case by case the results using the following main indexes (Recipe 2016):

- GWP—Global Warming Potential [kg CO_2/ha];
- PM—Fine Particulate Matter formation [kg PM 2.5/ha];
- FRS—Fossil Resource Scarcity [kg oil/ha];
- OD—Ozone Depletion [kg CFC11 eq/ha.];
- TA—Terrestrial Acidification [kg SO_2/ha].

In the following figures, the obtained results are reported with the standard deviation at a 95% confidence level.

The GWP for the three straw management methods is reported in Figure 6.

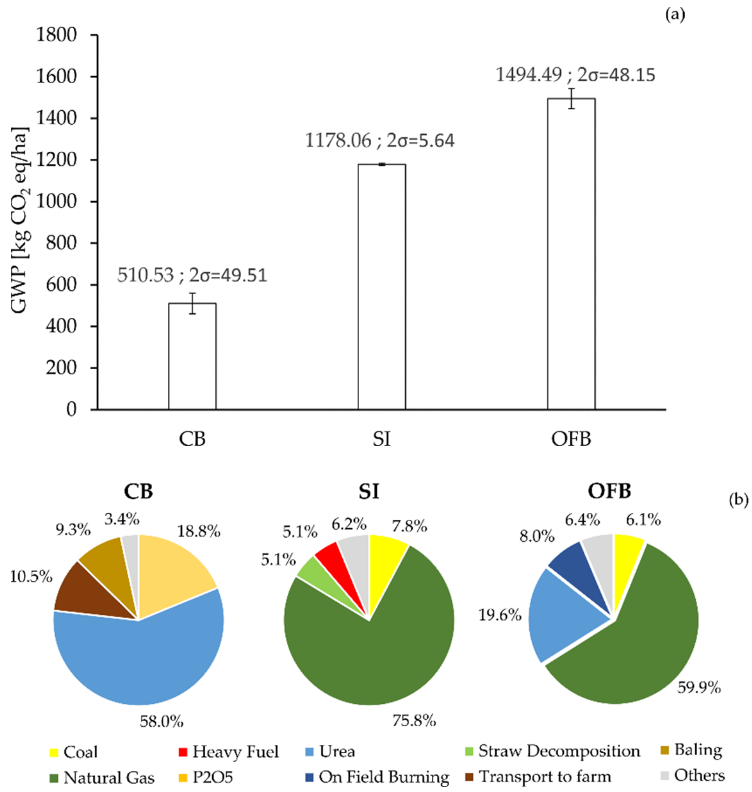

Figure 6. Global Warming Potential: (**a**) total amount, (**b**) percentage breakdown.

It can be easily assessed that CB presents the lowest value of CO_2 emissions with 510.53 kg eq/ha, while SI and OFB produce 1178.06 kg eq/ha and 1494.49 kg eq/ha of CO_2, respectively.

The breakdown analysis of the GWP indicates that for the CB practice, the main contributor is fertilization. About 296.1 kg eq/ha of the CO_2 production is due to the urea and about 96 kg eq/ha to the superphosphate due to their manufacturing processes. In the case of CB, the baling of the straw together with the transport to the farm account for about 101.1 kg eq/ha of CO_2.

In SI and OFB, because of the energy compensation applied (Figure 6), natural gas is the major contributor to GWP (about 892.9 kg eq/ha and 895.2 kg eq/ha, respectively). Fertilization with urea produces in OFB almost the same amount of CO_2 (293 kg eq/ha) produced in CB.

Regarding the emission of PM into the atmosphere, it can be seen from Figure 7 that the OFB represents the worst applicable strategy. In fact, this uncontrolled combustion in the open air releases an amount of 80.41 kg eq/ha of PM2.5, which is 74 times higher than that of the CB strategy and 62 higher than that of SI.

In the analysis of the distribution of the various contributions for the OFB, the fraction of PM formation, associated with natural gas for energy compensation, is negligible compared to the combustion process itself (78.9 kg/ha).

The most relevant contributions to the PM formation for both CB and SI are fertilizers (urea and superphosphate) and natural gas.

The third indicator examined is the FRS, which represents the use of non-renewable energy sources for various purposes. From Figure 8, it is clearly visible that the two processes involving the addition of fertilizers (CB and OFB) are those with the highest use of fossil resources.

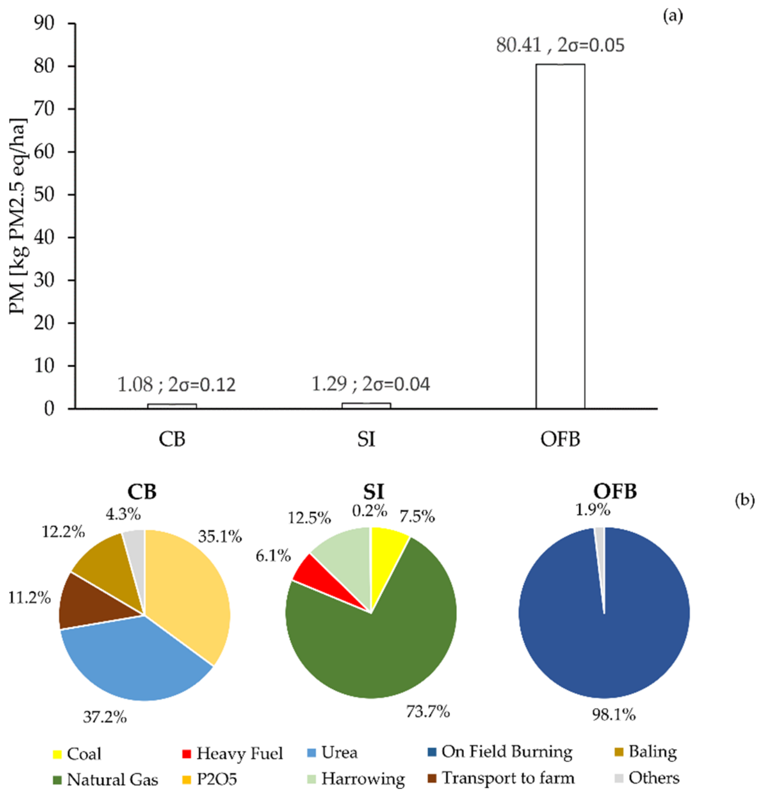

Figure 7. Particulate matter formation: (**a**) total amount, (**b**) percentage breakdown.

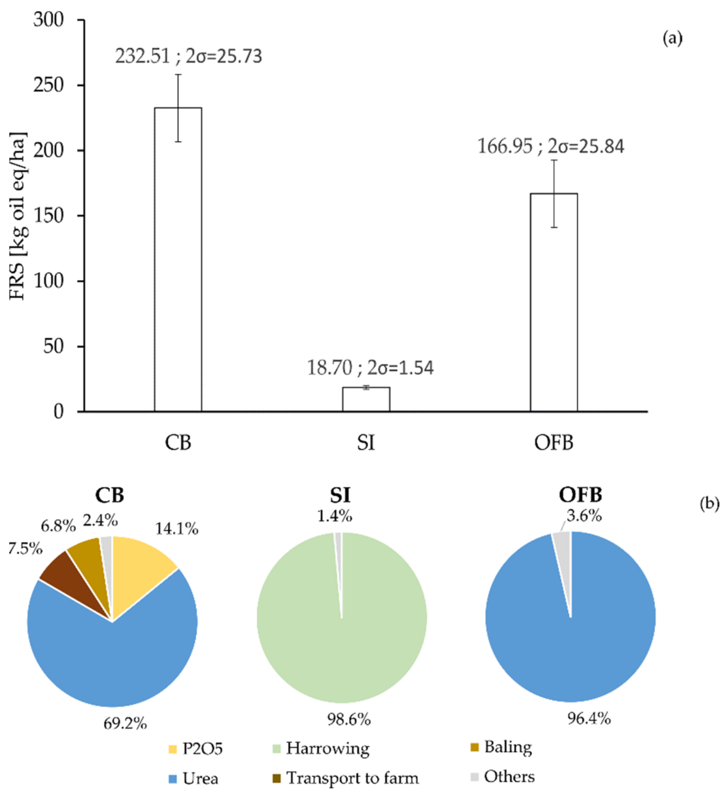

Figure 8. Fossil resource scarcity: (**a**) total amount, (**b**) percentage breakdown.

Indeed, the breakdown analysis shows that urea production is the major responsibility for the consumption of fossil fuels. This chemical process requires 69.2% of the total fossil fuel spent on CB (160.9 kg oil eq/ha) and 96.4% spent on OFB (160.9 kg oil eq/ha).

The second significant impact is represented by the production of P_2O_5, which requires 14.1% of the use of fossil resources in the CB scenario (about 32.8 kg oil eq/ha).

The OD index represents the quantity of ozone-depleting gases [54] produced by the anthropogenic transformation in equivalent kilograms of CFC11. Figure 9 shows that OFB is the practice that produces the greatest amount of harmful gases, which is 22 times more polluting than CB and 1.95 times than SI.

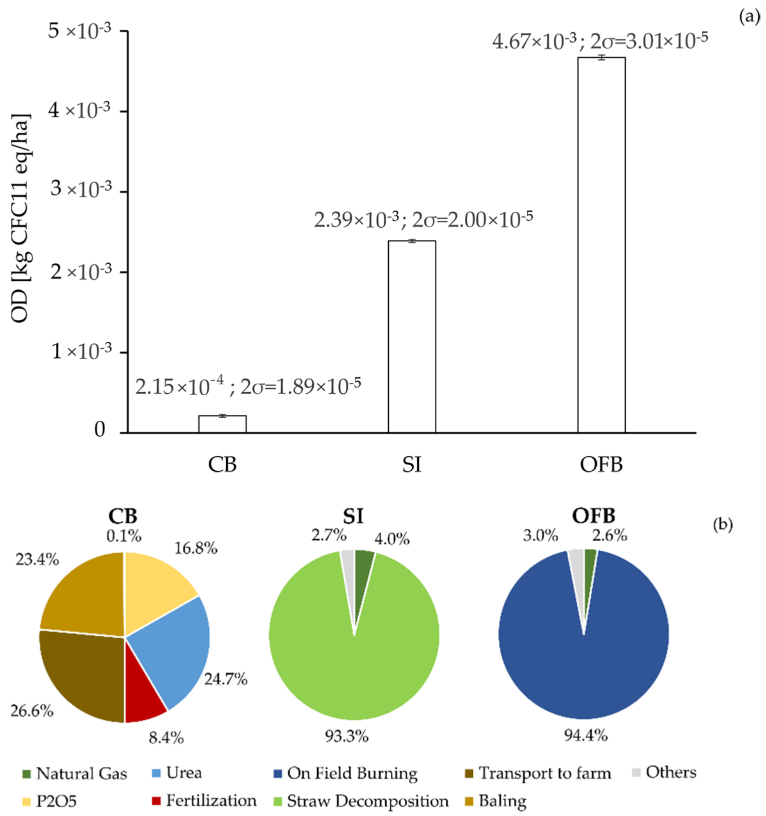

Figure 9. Stratospheric ozone depletion: (**a**) total amount, (**b**) percentage breakdown.

Based on the analysis of the various contributions, it emerges that the greatest contribution to the emission of CFC11 in the case of OFB is the combustion process (94.4%, i.e., 4.4×10^{-3} kg of CFC11/ha) while for the SI practice it is the decomposition of straw (93.3%, i.e., 2.2×10^{-3} kg of CFC11/ha). Natural gas contributes 1.2×10^{-4} kg/ha of CFC11 for OFB and 9.6×10^{-5} kg/ha for SI. For the CB scenario, urea production, baling and transport to the farm are responsible for approximately 25% each of CFC11 production (5.4×10^{-5} kg/ha).

Terrestrial acidification (Figure 10), expressed in equivalent mass of SO_2, reports the changes in the chemical properties of the soil following the deposition of both nutrients in acidifying forms and gases and particles from the atmosphere. The CB scenario shows the lowest impact in terms of SO_2 production (about 2.6 kg eq/ha), which is about half of that for OFB and about 63% of SI. In fact, the breakdown analysis shows how the energy compensation fraction with natural gas affects both OFB and SI practices with 3.2 kg SO_2 eq/ha.

Urea production represents the highest contribution in the CB scenario with 41.3% of total emissions (1.07 kg SO_2 eq/ha), while P_2O_5 is the second relevant contributor with 34.3% (0.9 kg SO_2 eq/ha).

Together these results provide important insights into the actual and possible straw management technique in Novara Province.

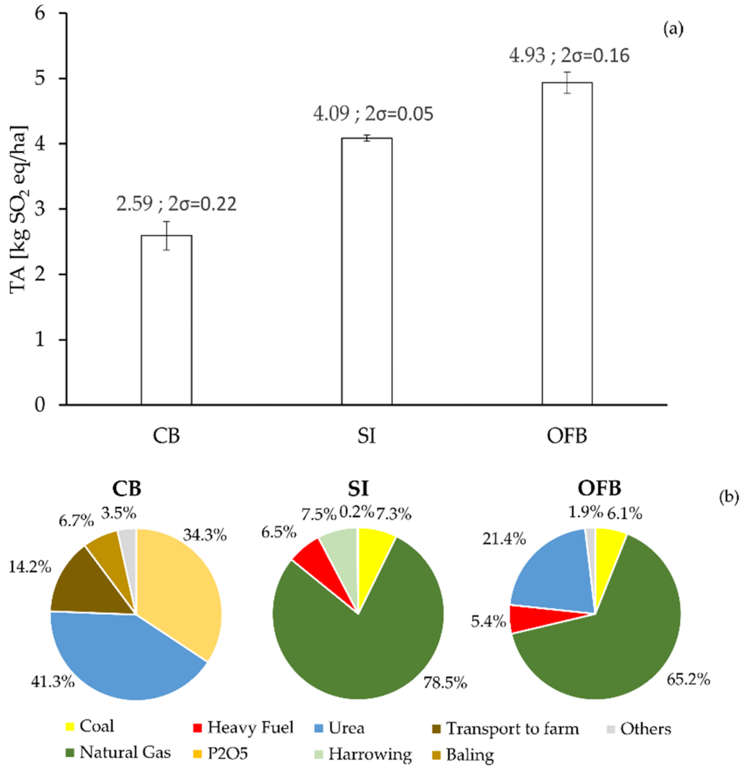

Figure 10. Terrestrial acidification: (**a**) total amount, (**b**) percentage breakdown.

In summary, among the three strategies, CB is the cleanest in relation to the PM formation, GWP, TA and OD indices. CB falls down in FRS because it needs a greater quantity of fertilizers (urea and P_2O_5) to compensate for the lack of organic materials that are not reintroduced into the soil (chopped rice straw in SI or ashes in OFB). Chemical fertilization is a cost-effective solution from an economic point of view but carries a significant environmental burden.

Among all the strategies, the worst is the OFB, which has the highest environmental impact for all the indicators except for FSR. Particular attention must be paid to the formation of PM in OFB because the geographical area object of this study is already affected by high concentrations of PM in the atmosphere [26–28].

SI (the more used rice management method in Novara) is a good choice to maintain the quality of the soil, and it requires a lower amount of fertilizers than CB. Notwithstanding this, from the analysis carried out, SI wins against CB only in relation to the FSR index. Moreover, considering the entire cultivation of rice, the incorporation of straw into the soil significantly increases the GHGs [19,33–35] and suggests thinking of a different disposal method.

LCA results allow us to evaluate the environmental impact linked to the waste of rice in the province of Novara, where in 2020 (actual scenario), the rice straw coming from over 33,000 ha underwent for about 70% to SI and for about 30% to OFB (Table 3).

Table 3. Actual scenario.

Straw Management	Land Use (ha)	PM (kg PM2.5 eq)	GWP (kg CO_2 eq)	TA (kg SO_2 eq)
OFB	9940.8	7.99×10^5	1.48×10^7	4.90×10^4
SI	23,195.2	0.30×10^5	2.73×10^7	9.49×10^4
Total	**33,136**	$\mathbf{8.29 \times 10^5}$	$\mathbf{4.21 \times 10^7}$	$\mathbf{14.39 \times 10^4}$

The environmental benefits related to the CB practice applied to the total amount of straw are shown in Table 4.

Table 4. CB vs. Actual scenario.

Straw Management	PM (kg PM2.5 eq)	GWP (kg CO_2 eq)	TA (kg SO_2 eq)
CB	0.36×10^5	1.69×10^7	8.58×10^4
OFB + SI	8.29×10^5	4.21×10^7	14.39×10^4
Difference	$\mathbf{-7.93 \times 10^5}$	$\mathbf{-2.52 \times 10^7}$	$\mathbf{-5.81 \times 10^4}$

Collecting and baling rice straw decreases by 96% PM production, 60% GWP and 40% the equivalent air emission of SO_2 compared to the actual rice straw management in Novara province.

5. Conclusions and Future Developments

The performed LCA analysis of the different rice straw management practices shows that Collection and Baling (CB) is a winning strategy in reducing the environmental impact of rice cultivation (−60% GWP, −40% TA and −96% PM).

Moreover, the energy harvesting from rice straw in northwest Italy can be a valuable alternative to the actual use of non-renewable resources such as coal, fuel oil and waste burning. In fact, applying the CB practice, an amount of energy of about 1.7 PJ might be obtained. The CB involves the production of cylindrical straw bales (1.8 m in diameter, 1.2 m in height and about 430 kg in weight) with an energy content of about 6 GJ each, which is the equivalent energy available from an oil barrel. For this reason, in analogy to what was conducted for oil, the concept of the straw barrel (i.e., the cylindrical bale previously defined) can be introduced, which allows us to estimate in over 280,000 straw barrels the carbon net neutral energy available in the province of Novara.

For energy conversion, the power plant located in the Novara suburbs could help to reduce the transport costs [15]. The opportunity offered by the location of this thermoelectric plant [30], together with the possibility of effective reuse of the silica contained in the combustion ashes [31], could be a reason for choosing this type of energy conversion.

It is suggestive to think that (considering a minimum overall efficiency for a conventional thermoelectric plant around 30% [55]), from the combustion of rice straw, it is possible to obtain up to 142 GWhe per year, sufficient to satisfy approximately 30% of the energy needs of the town of Novara.

In general, for the conversion of this biomass into energy, gasification [56], anaerobic digestion [57], pyrolysis [58], and ethanol production [59] could also be exploited.

Currently, this work presents some limitations. First, the LCA model does not take into account some important steps such as transportation to the plant for energy enhancement and the energy conversion process. Furthermore, the study does not evaluate and compare the environmental impact linked to the different energy conversion options of this carbon-neutral source.

Future investigations will be aimed both at the study of the agronomic changes to be applied for the sustainability of the CB and at the analysis of the value chain of this new path in order to identify the best energy conversion strategy.

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References

1. *Climate Change 2021: The Physical Science Basis. Summary for Policy Makers*; Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf (accessed on 9 August 2021).
2. New WHO Global Air Quality Guidelines Aim to Save Millions of Lives from Air Pollution. Available online: https://www.who.int/news/item/22-09-2021-new-who-global-air-quality-guidelines-aim-to-save-millions-of-lives-from-air-pollution (accessed on 22 September 2021).
3. Storey, G.; Meng, Q.; Li, B. Leaf Disease Segmentation and Detection in Apple Orchards for Precise Smart Spraying in Sustainable Agriculture. *Sustainability* **2022**, *14*, 1458. [CrossRef]
4. Akram, M.W.; Mohd Zublie, M.F.; Hasanuzzaman, M.; Rahim, N.A. Global Prospects, Advance Technologies and Policies of Energy-Saving and Sustainable Building Systems: A Review. *Sustainability* **2022**, *14*, 1316. [CrossRef]
5. Sirigu, S.A.; Foglietta, L.; Giorgi, G.; Bonfanti, M.; Cervelli, G.; Bracco, G.; Mattiazzo, G. Techno-Economic Optimisation for a Wave Energy Converter via Genetic Algorithm. *J. Mar. Sci. Eng.* **2020**, *8*, 482. [CrossRef]
6. Seglah, P.A.; Wang, Y.; Wang, H.; Neglo, K.A.W.; Gao, C.; Bi, Y. Energy Potential and Sustainability of Straw Resources in Three Regions of Ghana. *Sustainability* **2022**, *14*, 1434. [CrossRef]
7. Xiao, D.; Huang, C.; Luo, Y.; Tang, K.; Ruan, Q.; Wang, G.; Chu, P.K. Atomic-Scale Intercalation of Graphene Layers into $MoSe_2$ Nanoflower Sheets as a Highly Efficient Catalyst for Hydrogen Evolution Reaction. *ACS Appl. Mater. Interfaces* **2020**, *12*, 2460–2468. [CrossRef]
8. Wu, Y.; Luo, Y.; Qu, J.; Daoud, W.A.; Qi, T. Sustainable and shape-adaptable liquid single-electrode triboelectric nanogenerator for biomechanical energy harvesting. *Nano Energy* **2020**, *75*, 105027. [CrossRef]
9. United Nations Department of Economic and Social Affairs (UN DESA). *Sustainable Development Goal 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All*; UN DESA: New York, NY, USA, 2017.
10. IIASA. GEA, 2012: Global Energy Assessment—Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. Available online: https://iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html (accessed on 7 May 2021).
11. IEA. *The Role of Energy Efficiency*; IEA: Paris, France, 2018. Available online: https://www.iea.org/reports/the-role-of-energy-efficiency (accessed on 7 May 2021).
12. IRENA. *Global Energy Transformation: A Roadmap to 2050*; IRENA: Abu Dhabi, United Arab Emirates, 2018. Available online: https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition (accessed on 5 April 2019).
13. Shell Sky Scenario. 2017. Available online: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html (accessed on 7 May 2021).
14. Gielen, D.; Boshella, F.; Sayginb, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]
15. Torregrosa, A.; Giner, J.M.; Velázquez-Martí, B. Equipment Performance, Costs and Constraints of Packaging and Transporting Rice Straw for Alternative Uses to Burning in the "Parc Natural l'Albufera de València" (Spain). *Agriculture* **2021**, *11*, 570. [CrossRef]
16. Mofijur, M.; Mahlia, T.M.I.; Logeswaran, J.; Anwar, M.; Silitonga, A.S.; Rahman, S.M.A.; Shamsuddin, A.H. Potential of Rice Industry Biomass as a Renewable Energy Source. *Energies* **2019**, *12*, 4116. [CrossRef]
17. ISTAT (Italian National Institute of Statistics). Available online: https://www.istat.it/en/ (accessed on 5 April 2020).
18. Gadde, B.; Bonnet, S.; Menke, C.; Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environ. Pollut.* **2009**, *157*, 1554–1558. [CrossRef]
19. Romasantaa, R.R.; Sandera, B.O.; Gaihrea, Y.K. How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices. *Agric. Ecosyst. Environ.* **2017**, *239*, 143–153. [CrossRef]
20. Yodkhum, S.; Sampattagul, S.; Gheewala, S.H. Energy and environmental impact analysis of rice cultivation and straw management in northern Thailand. *Environ. Sci. Pollut. Res.* **2018**, *25*, 17654–17664. [CrossRef] [PubMed]
21. Decision 2000/532/EC. Available online: https://op.europa.eu/en/publication-detail/-/publication/239a2785-9115-4e06-adae-66c8e08a5a42 (accessed on 3 March 2020).
22. WHO. Health Effects of Particulate Matter Policy Implications for Countries in Eastern Europe, Caucasus and Central Asia. Available online: https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf (accessed on 5 April 2013).
23. Directive 2008/50/EC of the European Parliament and of the Council. 21 May 2008. Available online: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32008L0050 (accessed on 5 April 2013).
24. Directive 2004/35/EC of the European Parliament and of the Council. 21 April 2004. Available online: https://www.legislation.gov.uk/eudr/2004/35/contents (accessed on 21 April 2004).

25. Piano Regionale Qualità Aria Allegato1_def. Available online: https://www.regione.piemonte.it/web/temi/ambiente-territorio/ambiente/aria/piano-regionale-qualita-dellaria-prqa (accessed on 25 March 2019).
26. Schroeder, P.; Belis, C.A.; Schnelle-Kreis, J.; Herzig, R.; Prevot, A.S.H.; Raveton, M.; Kirchner, M.; Catinon, M. Why air quality in the Alps remains a matter of concern? The impact of organic pollutants in the alpine area. *Environ. Sci. Pollut. Res.* **2014**, *21*, 252–267. [CrossRef] [PubMed]
27. Paglione, M.; Gilardoni, S.; Rinaldi, M.; Decesari, S.; Zanca, N.; Sandrini, S.; Giulianelli, L.; Bacco, D.; Ferrari, S.; Poluzzi, V.; et al. The impact of biomass burning and aqueous-phase processing on air quality: A multi-year source apportionment study in the Po Valley, Italy. *Atmos. Chem. Phys.* **2020**, *20*, 1233–1254. [CrossRef]
28. Diémoz, H.; Gobbi, G.P.; Magri, T.; Pession, G.; Pittavino, S.; Tombolato, I.K.F.; Campanelli, M.; Barnaba, F. Transport of Po Valley aerosol pollution to the northwestern Alps—Part 2: Long-term impact on air quality. *Atmos. Chem. Phys.* **2019**, *19*, 10129–10160. [CrossRef]
29. Prespa, Y.; Csaba, G.; Csaba, F. Farmers' Attitudes Towards the Use of Biomass as Renewable Energy—A Case Study from Southeastern Europe. *Sustainability* **2020**, *12*, 4009. [CrossRef]
30. Liu, Z.; Xu, A.; Zhao, T. Energy from Combustion of Rice Straw: Status and Challenges to China. *Int. J. Power Energy Eng.* **2011**, *3*, 325–331. [CrossRef]
31. Moliner, C.; Bove, D.; Arato, E. Co-Incineration of Rice Straw-Wood Pellets: A Sustainable Strategy for the Valorisation of Rice Waste. *Energies* **2020**, *13*, 5750. [CrossRef]
32. UNI EN ISO 14040:2021—Environmental Management—Life Cycle Assessment—Principles and Framework. Available online: http://store.uni.com/catalogo/home (accessed on 18 February 2021).
33. IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 5: Cropland. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_05_Ch5_Cropland.pdf (accessed on 1 July 2006).
34. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf (accessed on 1 July 2006).
35. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2: Stationary Combustion. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf (accessed on 1 July 2006).
36. Anshassi, M.; Townsend, T. Reviewing the underlying assumptions in waste LCA models to identify impacts on waste management decision making. *J. Clean. Prod.* **2021**, *313*, 127913. [CrossRef]
37. Ferrero, A.; Tinarelli, A. Rice Cultivation in the E.U. Ecological Conditions and Agronomical Practices. In *Pesticide Risk Assessment in Rice Paddies*; Capri, E., Karpouzas, D.G., Eds.; Elsevier: Amsterdam, The Netherlands, 2008; Volume 1, pp. 1–24. [CrossRef]
38. Song, H.J.; Lee, J.H.; Jeong, H.C.; Choi, E.J.; Oh, T.K.; Hong, C.O.; Kim, P.J. Effect of straw incorporation on methane emission in rice paddy: Conversion factor and smart straw management. *Appl. Biol. Chem.* **2019**, *62*, 70. [CrossRef]
39. IPCC—National Greenhouse Gas Inventories Programme. Background Papers—IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories—CH_4 Emissions from Rice Agriculture. 2002, pp. 399–417. Available online: https://www.ipcc-nggip.iges.or.jp/public/gp/gpg-bgp.html (accessed on 5 April 2002).
40. Linquist, B.A.; Adviento-Borbe, M.A.; Pittelkow, C.M.; van Kessel, C.; van Groenigen, K.J. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crop. Res.* **2012**, *135*, 10–21. [CrossRef]
41. Ente Nazionale Risi. Available online: http://www.enterisi.it/servizi/Menu/dinamica.aspx?idSezione=17505&idArea=17548&idCat=17551&ID=17551&TipoElemento=categoria (accessed on 31 January 2022).
42. Porichha, G.; Hu, Y.; Rao, K.; Xu, C. Crop Residue Management in India: Stubble Burning vs. Other Utilizations including Bioenergy. *Energies* **2021**, *14*, 4281. [CrossRef]
43. Saothongnoi, V.; Amkha, S.; Inubushi, K.; Smakgahn, K. Effect of Rice Straw Incorporation on Soil Properties and Rice Yield. *Thai J. Agric. Sci.* **2014**, *47*, 7–12.
44. Chivenge, P.; Rubianes, F. Rice Straw Incorporation Influences Nutrient Cycling and Soil Organic Matter. In *Sustainable Rice Straw Management*; Gummert, M., Van Hung, N., Chivenge, P., Douthwaite, P., Eds.; SpringerOpen: New York, NY, USA, 2020; pp. 131–144. [CrossRef]
45. Zhao, X.; Yuan, G.; Wang, H.; Lu, D.; Chen, X.; Zhou, J. Effects of Full Straw Incorporation on Soil Fertility and Crop Yield in Rice-Wheat Rotation for Silty Clay Loamy Cropland. *Agronomy* **2019**, *9*, 133. [CrossRef]
46. Roselló, J.; Soriano, L.; Santamarina, M.P.; Akasaki, J.L.; Monzó, J.; Payá, J. Rice straw ash: A potential pozzolanic supplementary material for cementing systems. *Ind. Crop. Prod.* **2017**, *103*, 39–50. [CrossRef]
47. Sander, B.O.; Samson, M.; Buresh, R.J. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma* **2014**, *235–236*, 355–362. [CrossRef]
48. Dyjakon, A.; den Boer, J.; Szumny, A.; den Boer, E. Local Energy Use of Biomass from Apple Orchards—An LCA Study. *Sustainability* **2019**, *11*, 1604. [CrossRef]
49. Gadde, B.; Menke, C.; Wassmann, R. Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. *Biomass Bioenergy* **2009**, *33*, 1532–1546. [CrossRef]
50. Gargiulo, A.; Carvalho, M.L.; Girardi, P. Life Cycle Assessment of Italian Electricity Scenarios to 2030. *Energies* **2020**, *13*, 3852. [CrossRef]

51. Pandey, A.; Kumar, B. Analysis of rice straw ash for part replacement of OPC in pavement quality concrete. *Int. J. Adv. Mech. Civ. Eng.* **2016**, *3*, 1–4. Available online: https://www.researchgate.net/publication/311580594 (accessed on 5 June 2016).
52. Giardini, R. *Coltivazioni Erbacee*; Pàtron Editore: Bologna, Italy, 2010.
53. Wang, J.; Chen, X.; Wei, J. Decomposition of Rice Straw and Corn Straw Under Aerobic and Anaerobic Conditions. *J. Agric. Resour. Environ.* **2017**, *34*, 59–65. [CrossRef]
54. Lane, J.L. Stratospheric Ozone Depletion. In *Life Cycle Impact Assessment*; Hauschild, M., Huijbregts, M., Eds.; Springer: Dordrecht, The Netherlands, 2015; pp. 51–73. [CrossRef]
55. Putrus, G.; Bentley, E. Integration of distributed renewable energy systems into the smart grid. In *Renewable Energy Systems*; Rashid, M.H., Ed.; Academic Press: London, UK, 2016.
56. Shie, J.L.; Chang, C.Y.; Chen, C.S.; Shaw, D.G.; Chen, Y.H.; Kuan, W.H.; Ma, H.K. Energy life cycle assessment of rice straw bio-energy derived from potential gasification technologies. *Bioresour. Technol.* **2011**, *102*, 6735–6741. [CrossRef] [PubMed]
57. Nguyen, V.H.; Topno, S.; Balingbing, C.; Nguyen, V.C.N.; Röder, M.; Quilty, J.; Jamieson, C.; Thornley, P.; Gummert, M. Generating a positive energy balance from using rice straw for anaerobic digestion. *Energy Rep.* **2016**, *2*, 117–122. [CrossRef]
58. Huang, Y.F.; Kuan, W.H.; Lo, S.L.; Lin, C.F. Total recovery of resources and energy from rice straw using microwave-induced pyrolysis. *Bioresour. Technol.* **2008**, *99*, 8252–8258. [CrossRef] [PubMed]
59. Soam, S.; Kapoor, M.; Kumar, R.; Borjesson, P.; Gupta, R.P.; Tuli, D.K. Global warming potential and energy analysis of second generation ethanol production from rice straw in India. *Appl. Energy* **2016**, *184*, 353–364. [CrossRef]