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Research article

Unlocking the power of Italy's bioeconomy: A comparative analysis of immediate vs. deferred impact on energy generation through straw valorisation

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A B S T R A C T

This study investigates the value and impacts of utilising cereal residual biomass according to bioeconomy principles within the Italian context. Cereals are relevant in Italy, accounting for over 60 % of total crop residue production. These residues exhibit uniform energy content, enabling different applications. This study uniquely compares three scenarios for converting straw residues into bioenergy via combustion, slow pyrolysis, and anaerobic digestion, considering residues availability and environmental impacts assessed through attributional Life Cycle Assessment (ISO 14040-44) using 1 GJ of energy obtained as a functional unit. Each investigated scenario is based exclusively on using cereal residual biomasses without adding other residual biomasses and includes both the production of bioenergy and the contribution to carbon stocks, considering the residues left in the field and the potential return of biochar. Among the scenarios, slow pyrolysis emerged as the most promising, with biochar offering additional yet unquantified benefits for carbon-smart management, climate change mitigation, and economic sustainability. The potential benefits of pyrolysis and biochar underscore the positive outcomes of the study, which are instrumental in guiding the development of regulatory frameworks supporting policymakers in making sustainable decisions. By providing a detailed comparison of environmental impacts, this research integrates effective cereal residue management practices into policy and regulatory measures, highlighting promising solutions and directing further research toward maximising environmental and climate benefits through optimised and targeted approaches.

1. Introduction

Energy is vital for the sustainability of modern society, with increasing demands driven by population growth and economic activities (Jie et al., 2023). Coal, oil, and natural gas dominate the global energy supply, contributing around 81 % (Anand et al., 2023). However, concerns over environmental impacts, such as Greenhouse Gas (GHG) emissions, climate change, and health risks, necessitate searching for eco-friendly alternatives (Gasparotto and Da Boit Martinello, 2021). The Intergovernmental Panel on Climate Change (IPCC) urges nations to reduce carbon dioxide (CO_2) emissions to zero by 2050 to limit global warming to 1.5 °C (IPCC, 2022). In response, there is a growing interest in renewable energy sources like lignocellulosic biomasses, spurred by the depletion of coal reserves and rising energy costs, aiming to replace crude oil-based petro-refinery products. Bioenergy is the largest renewable energy source globally, accounting for 55 % of renewable energy and over 6 % of the global energy supply (International Energy Agency, 2024a,b). In Europe, bioenergy derived from agricultural, forestry, and organic waste feedstock remains the primary source of renewable energy, constituting approximately 59 % of renewable energy consumption in 2021 (European Commission, 2024; Kapoor et al., 2020a). Among bioenergy sources, primary solid biofuels hold the largest share, accounting for 70.3 %. In comparison to fossil fuels, biomass has the potential to reduce direct GHG emissions (European Commission, Directorate-General for Energy, 2023); however, its overall life cycle implications are less specific (Malico et al., 2016). The effects of biomass extraction from the environment vary in nature and extent depending on the production system employed, introducing trade-offs with other ecosystem services (Makkonen et al., 2015). Moreover, while biofuels like biodiesel, bioethanol, and biogas were traditionally sourced from 1st generation feedstocks such as oil seeds, corn, sugarcane juice, and molasses, the debate surrounding food versus fuel has shifted the focus to 2nd generation feedstocks, namely lignocellulosic feedstock, primarily derived from agro-residues (Kapoor et al., 2020b). Research indicates biofuel production offers significant benefits, mainly from agricultural residues and wastes (Awogbemi and Kallon, 2022; Sikiru

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et al., 2024). These materials are cost-effective, abundant, renewable, and easily degradable. Therefore, agricultural waste has emerged as a prominent alternative energy source, addressing economic and environmental concerns. Several studies have examined the potential adverse environmental impacts of bioenergy from 1st generation feedstock (Wang et al., 2018), while, through comparative life cycle assessment studies, other researchers have demonstrated that utilising biomass residues for energy production could be environmentally beneficial and have a lower impact compared to using dedicated energy crops (Saberi et al., 2024).

Cereals are relevant crops in terms of both cultivated area and production in Italy, in which arable land represents 57 % of the Utilised Agricultural Area (UAA) and within the arable land, cereals and fodder crops were found to be the two main categories of production (EUROSTAT, 2013). Moreover, cereals contribute the majority of crop residue production and account for over 60 % of the total unharvested output (European Commission, 2018). Residues from cereals production exhibit relatively uniform energy and protein content, facilitating their diverse potential uses that include animal feed or bedding, off-field applications such as domestic fuel, industrial purposes, mushroom cultivation or construction, and on-field retention (Martinov et al., 2008). The scientific literature offers various suggestions on how crop residue management could address urgent global issues (Hakala et al., 2009; Lal, 2012; Scarlat et al., 2010), such as climate change and the depletion of organic matter. These suggestions include replacing some fossil fuels with bioenergy derived from crop residues, maintaining a higher portion of crop residues in the field to boost soil organic carbon (SOC) stocks, and substituting human-edible grains in animal diets with crop residues to reduce the need for cropland. However, evaluating the effectiveness of these proposals is challenging due to limited knowledge about current crop residue utilisation, resulting in an uncertain baseline and complicating the assessment of trade-offs associated with allocating more crop residues to specific uses. In addition, the yields of annual crops can vary considerably from year to year, especially at a local level, due to precipitation patterns in rain-fed conditions, resulting in variability in crop residue production (García-León et al., 2020; Smerald et al., 2023). The quantity of residues is closely linked to crop production, determined by yield and cultivated area. The availability of residues hinges on factors such as the amount that can be safely removed from land to maintain soil fertility and competing demands for agricultural or industrial uses. Crop residues remaining on the field could be significant sources of carbon and nitrogen in farming soils, contributing to the maintenance or improvement of SOC stocks. This, in turn, reduces the susceptibility of plant growth to drought, lowers erosion rates and enhances soil aeration (Scarlat et al., 2010). Utilising agricultural crop residues for bioenergy production, such as straw or stover (comprising stalks, ears, leaves, or cobs), necessitates accurate data on their availability by crop type, alongside consideration of their local and annual variations (Liu et al., 2014). Estimating the residues available for bioenergy production offers insights into optimal plant locations and informs decisions regarding plant type and size.

Cereal residues are lignocellulosic biomasses that can be converted into various end-products through different conversion methods (Segers et al., 2024). These end-products are classified into four categories: fuels/energy, materials, platform chemicals, and biochar. The first category focuses on energy production through processes like combustion, gasification, or fermentation, which help reduce greenhouse gas emissions and dependence on fossil fuels, making them essential resources (Islam et al., 2024; Saleem, 2022; Demichelis et al., 2025 analysed the Italian context to identify the availability and the features of thermochemical and biological treatment plants. Some of these technologies are presented as being the most promising due to their higher Technology Readiness Level (TRL) and greater widespread adoption in Italy. Thermochemical processes include combustion, pyrolysis and gasification. Combustion directly converts energy stored in chemical bonds of biomass into heat and, consequently, into electricity, providing a readily deployable technology (Nussbaumer, 2003; Sivabalan et al., 2021). On the other hand, pyrolysis and gasification are processes that convert biomass into different amounts of biochar, syngas and bio-oil using different temperatures (350–800 °C) and in the absence or in the presence of a limited amount of oxygen, respectively (Basu, 2018). Pyrolysis encompasses various methods: slow pyrolysis is favoured for its operation at atmospheric pressure and the highest biochar production that can be used as a soil amendment, while fast pyrolysis stands out due to its superior energy conversion efficiency (Joshi et al., 2024). Anaerobic digestion is a biological process where microorganisms, without oxygen, convert biomass into biogas (Khalid et al., 2011). This biogas is a mixture of methane and carbon dioxide that can be used as an energy resource. Straw has not been a favoured substrate for energy production due to its complex lignocellulosic structure, which hinders decomposition. In fact, in one side straw is rich in cellulose and has a nutritional composition suitable for microbial growth and biogas production, but, in the other, using straw alone in could be not economically viable due to its high carbon-to-nitrogen (C/N) ratio that limits biogas production by restricting nitrogen availability for cellular synthesis and the proper functioning of methanogenic bacteria. However, the rising need to reduce abundant biomass waste and the growing demand for renewable energy have driven advancements in processing techniques and the development of suitable inoculum and pretreatment methods. Pretreatment methods, including physical, chemical, biological, and combined approaches, are key to overcoming kinetic limitations in anaerobic digestion and enhancing biogas production from lignocellulosic biomass (Luo et al., 2019; Mussoline et al., 2013; Yu et al., 2019). Some authors advocate for the co-digestion of straw to increase yields (Rahmani et al., 2022; Sarkar et al., 2024). This process involves the simultaneous anaerobic digestion of a mixture of two or more substrates in a bioreactor to enhance biogas production by adding substrates with higher methane (CH_4) potential (Kainthola et al., 2019; Kamusoko and Mukumba, 2024; Mothe and Polisetty, 2021). The digestate remaining after digestion is a slurry that can be used as a fertiliser (Meegoda et al., 2018). While digestate offers valuable agricultural benefits, such as nutrient enrichment comparable to mineral fertilisers (Riva et al., 2016; Simon et al., 2015), biochar, a stable carbon-rich pyrolysis product, presents several distinct advantages as a soil amendment. Biochar application to soils holds significant potential, offering a range of benefits, including enhanced soil quality, improved plant growth, potential for disease suppression, and the capacity to remove pollutants (Ding et al., 2017). However, realising these benefits is contingent upon a nuanced understanding of several critical factors: the source of biomass used to produce biochar, the pyrolysis temperature employed, the rate of biochar application, and the specific soil and environmental conditions all play crucial roles in determining the actual outcomes. Consequently, the role of biochar in agricultural soils remains an area of active research, with its effectiveness often contingent upon specific and carefully considered applications. Moreover, Italy's diverse topography leads to various agricultural products, with cereals, legumes, and potatoes exhibiting the highest average theoretical energy potential (Di Fraia et al., 2020).

Based on the preceding considerations, several vital insights emerge: i) it is imperative to accurately assess the energy potential of agricultural residues biomass resources on a national scale; ii) the relationship between bioenergy and the environment is intricate and multifaceted; iii) utilising agricultural residues streams appears to offer favourable environmental outcomes. Considering these examinations, this study investigates the environmental impacts of cereal residual biomass utilisation in Italy. The current research aimed to quantify the untapped potential of residual agricultural biomass in Italy, highlighting its potential for multifaceted benefits. This evaluation considers each method's avoided emissions and carbon stock. The LCA was used as an environmental performance tool, with the assessment aimed at preliminary eco-design (Spósito et al., 2023). Eco-design is defined as the integration of life cycle options for a system and its components, where the design solution is determined by evaluating the environmental impact of alternative options. Therefore, the findings from this research aim to support the integration of effective and sustainable straw management practices into policy and regulatory measures, which can be instrumental in developing regulatory frameworks and guiding policymakers, providing a detailed comparison of the environmental impacts. Moreover, the study highlights the most promising solutions, addressing further research towards optimising the approaches and maximising their climate benefits.

2. Material and methods

2.1. Cereal residues estimation

The data concerning cereal harvest were obtained from the Italian Institute of Statistics ISTAT for the seasons 2019–2023 (ISTAT, 2024). A factor (PP01) specific to each type of cereal sourced from literature (Laurentiis and Caldeira, 2021) was applied to the harvest data to estimate the total production. This coefficient PP01, also known as the "side flow coefficient" (Hartikainen et al., 2017), represents the portion of the total crop ready for harvest that is either wasted, lost, transformed into animal feed, or other by-products. It is a crucial factor in estimating the amount of agricultural residues available for energy valorisation. Subsequently, the overall "side flow" was obtained by subtracting the harvested quantity from the total yield.

The different utilisation of side flow from cereals in Italy was derived from the publication by Femia and Manzi (2016). This manuscript determined the percentages of side flow used (within and outside the holding) and unused (wasted and left on soil). For this study, only the portion 'left on soil' was considered to determine the 'available to be used' fraction. Considering an alternative use for what is already being utilised would have resulted in a consequential LCA study, where the goal is to describe the changes in environmentally relevant flows in response to potential decisions (Finnveden et al., 2009), requiring the use of marginal data that is difficult to obtain. Therefore, the 'left on soil' portion was considered, and if this exceeded the quantity suggested by literature for maintaining soil organic matter, soil organic carbon, and protection against erosion (Scarlat et al., 2010), the surplus (the 'available to be used' portion) was allocated to energy valorisation scenarios as described in the following section.

2.2. Scenarios definition

Three main scenarios have been constructed to compare the potential environmental impacts of alternative methods for the energy valorisation of the "available to be used" portion of the cereal residues, selecting technologies already discussed in the literature and already potentially available for practical use in Italy. For this reason, field combustion has not been considered due to its harmful environmental and health effects, unlike Palmieri et al. (2017). Although it is common to mix different feedstocks for energy valorisation (Gusiatin, 2024; Magdziarz et al., 2024; Rahmani et al., 2022; Sahu et al., 2014; Sarkar et al., 2024), the current work aims to analyse the possible valorisation of cereal residues in Italy without mixing them with other potential residual biomasses, as their addition would alter the comparison and fall outside the scope of this paper. Among the technologies available in Italy, as presented by Demichelis et al. (2025), the three thermo-chemical and biological technologies discussed below were selected not only because they are available but also because they have the highest TRL (TRL >4) and apply to cereal residues, that are the most widely available agricultural residues in Italy.

Scenarios are described below:

SC1: "Available to be used" fraction of residues is directly combusted to produce heat. Chopping and ploughing of straw are not taken into consideration because the most common machine-tractor units perform the following technological operations simultaneously: (i) chopping plant residues and (ii) ploughing and covering the chopped stubble with the soil. The combustion is modelled in a furnace of 300 kW capacity for heat production. SC1 consists of collecting, baling, transporting, and granulating residual straw, followed by its use in the furnace, where all the energy inputs and emissions are considered.

SC2: "Available to be used" fraction of residues is valorised in a slow pyrolysis plant operating between 300 and 550 °C to produce biochar, syngas, and bio-oil in less than 10 min. Biochar is returned to the soil. The pyrolysis process has been modelled considering five stages, such as collecting and baling the feedstocks, conveying the feedstocks to the pyrolysis plant, granulating the straw before the pyrolysis, scrubbing the gases to remove the particulates, water, hydrocarbons and soluble matters, and using the outputs to generate heat. SC2B: All the residues left on the soil are used in a slow pyrolysis plant as in the SC2 to produce biochar, syngas and bio-oil. Biochar is returned to the soil.

SC3 "Available to be used" fraction of residues is used in an anaerobic digestor, with alkali pretreatment, to produce heat, and the digestate is returned to the soil. A large-scale biogas plant with a volume of 600 m^3 was considered. The following phases have been included: chopping into small pieces (3–5 cm), mixing with water and chemical pre-treatment with 3 % sodium hydroxide (NaOH) with an efficiency of 88 %, and then the digestion process for biogas production at mesophilic conditions (~35 °C) (Andersen et al., 2022).

In all the scenarios, a mass loss of 1 % was assumed for transporting biomass feedstock to the plants, with an additional 3.00 % mass loss for SC2 and SC2B due to the transport of biochar to the field, according to Yang (2021).

The assortment of outputs may exhibit notable variations depending on the chosen feedstocks and pyrolysis methods. In scenarios SC2 and SC2B, a slow pyrolysis plant has been simulated, wherein it is projected that different percentages of feedstock carbon (28 %, 32 %, and 40 %) would result in bio-oil, syngas and biochar, respectively (Gong and Kung, 2021).

2.3. LCA analysis

In this study, the Life Cycle Assessment (LCA) methodology followed the international approach proposed by ISO (ISO 14040, 2006; ISO 14044, 2006). LCA is employed to assess the environmental impacts arising from the implementation of various scenarios for the energy valorisation of residues harvested from cereal temporary crops in Italy between 2019 and 2023. As described in ISO/TR 14049, a system expansion approach has been employed to address the multi-functionality in the selected scenarios. This approach avoids allocation processes, which aligns with ISO 14040 and ISO 14044 recommendations. To accomplish this goal, the heat produced is considered to substitute the same amount produced in Italy in a combined cycle power plant in a heat and power cogeneration plant using natural gas (400 MW electrical). Moreover, in the SC3, digestate is considered to substitute a nitrogen-equivalent amount of organic fertilisers (see Fig. 1). This amount has been calculated assuming from Andersen et al. (2022), that the 70 % of cereal residues (D.M.) is transformed into digestate solid fraction, with a 0.3 % nitrogen content according to Nyang'au et al., 2023. Avoided products have been related respectively according to the following processes: heat, district or industrial, natural gas {IT}| heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical | APOS, U; inorganic nitrogen fertiliser, as N {IT}| market for inorganic nitrogen fertiliser, as N | APOS, U from the Ecoinvent 3.8 database.

The functional unit used to assess the effectiveness of the various scenarios is the production of 1 GJ of heat generated within each scenario.

The system boundaries include the stages and associated processes of the energetic valorisation of residual biomasses (Fig. 2). Therefore, the stages considered in this LCA study are listed in the following:

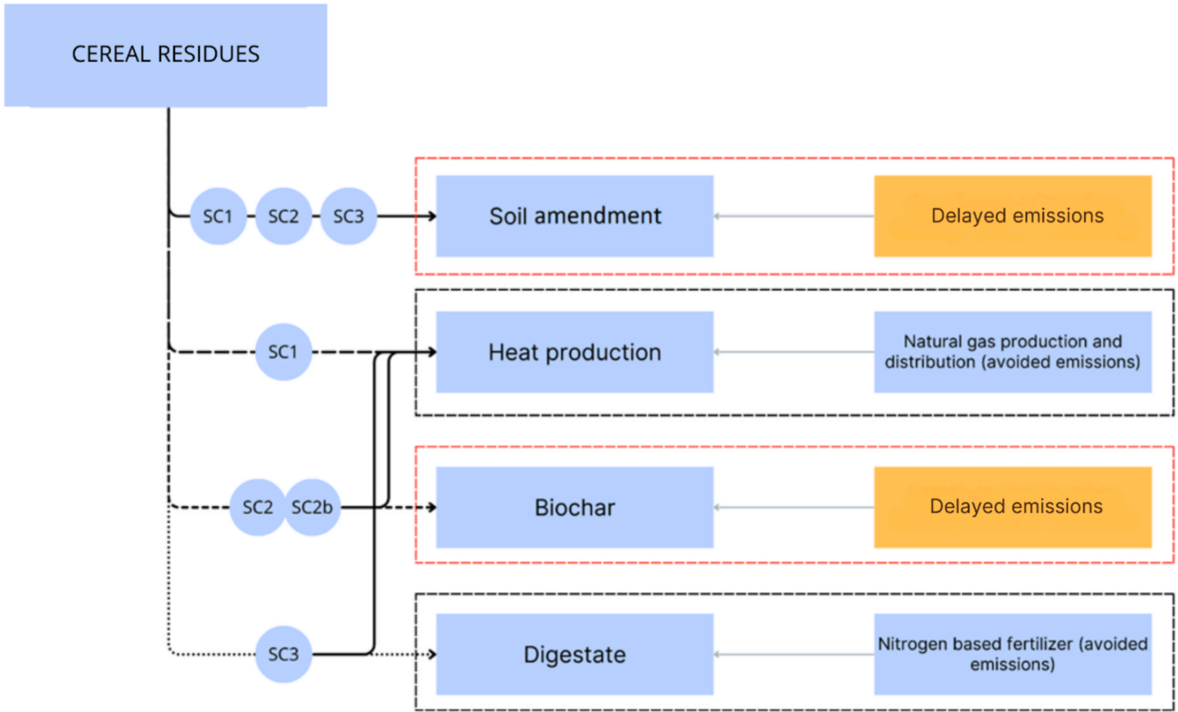

Fig. 1. System expansion description. (SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion. SC1, SC2, and SC3 convert only the "available to be used" fraction, while SC2B includes the Slow Pyrolysis of all the cereal residues).

- Baling and transporting the residual biomasses to the energy valorisation plants.
- Operating the valorisation plants, encompassing both material and energy inputs needed into the selected processes (chopping, pretreatment, etc.).
- Distributing and applying the biochar and the digestate to the fields.
- Calculate the carbon stock from residual biomasses on the soil and from biochar application.
- Calculating the reduction in the production of inorganic nitrogen fertilisers due to digestate application.

These LCA processes are excluded from the system boundaries:

- Primary production from which residual biomasses are obtained. All agricultural inputs required for crop cultivation are not considered, as they are assumed to be fully allocated to the grains. All the energy valorisation methods are off-field management approaches. Therefore, the environmental impacts of the stages before collection, including cultivation, harvesting, and land-use changes, are outside the scope of this study (Cherubini and Ulgiati, 2010).
- Capital investment details about the different energy valorisation plants such as purchased buildings and service facilities, engineering and supervision, operation and maintenance. This study aims to assess the impact of heat production processes from residual biomasses, excluding the environmental effects associated with the plants' infrastructure, maintenance, human labour, and capital expenditure (Alengebawy et al., 2022; Samer et al., 2021).

Therefore, the study is from cradle to gate, considering that the transmission and distribution grid are excluded from the analysis and the disposal of the resulting waste. The second phase in the LCA consists of an inventory of the system's input/output data under investigation. Then, it involves collecting the data necessary to achieve the study's goal (ISO 14040, 2006). The data in this LCA study consists mainly of secondary data. The secondary data are collected from the Ecoinvent 3.8 database and previous literature, as reported in Table 1, which shows, related to one average year, the specific inventory data (input and output) relating to the energetic valorisation of residual biomasses from temporary crops (cereals) in Italy.

The different scenarios were modelled on SimaPro® software, version 9.4.0.1 (PRé Consultants B.V., Amsterfoort, The Netherlands) using Ecoinvent 3.8 (Ecoinvent, Zurich, Switzerland) as the dataset for background data. All background data from Ecoinvent used the allocation at point of substitution (APOS) approach. Environmental impacts were determined according to the EF 3.0 Method. Normalised and weighted results were derived using the Single Score, developed by the European Commission as part of the Product Environmental Footprint (PEF) methodology. This approach utilises a set of normalisation and weighting factors to compute an aggregated final score. Here, the reference framework for normalisation values is based on the environmental impact of all goods and services within the European Union (European Commission, 2013; Sala et al., 2017).

2.4. Sensitivity analysis

Sensitivity analysis is critical for revealing the reliability and robustness of LCA. A sensitivity analysis was conducted to identify the influential variability for the most effective scenario. For this study, the sensitivity factors included transport distance and biochar production, considering that all the other inputs considered in the LCA analysis are a function of the residual biomass entering the valorisation process. Two distances (100 km and 10 km) and two biochar yields (40 % and 12 % of initial biomass) were used for uncertain scenarios and compared with the studied scenario. Variance-based sensitivity analyses have been conducted to understand the results' variability and help identify which input factors contribute most to this variability. The sensitivity analyses were conducted using the risk analysis software @Risk.5.5 (Palisade Corp).

3. Results and discussion

The histogram in Fig. 3 provides a comprehensive breakdown of the

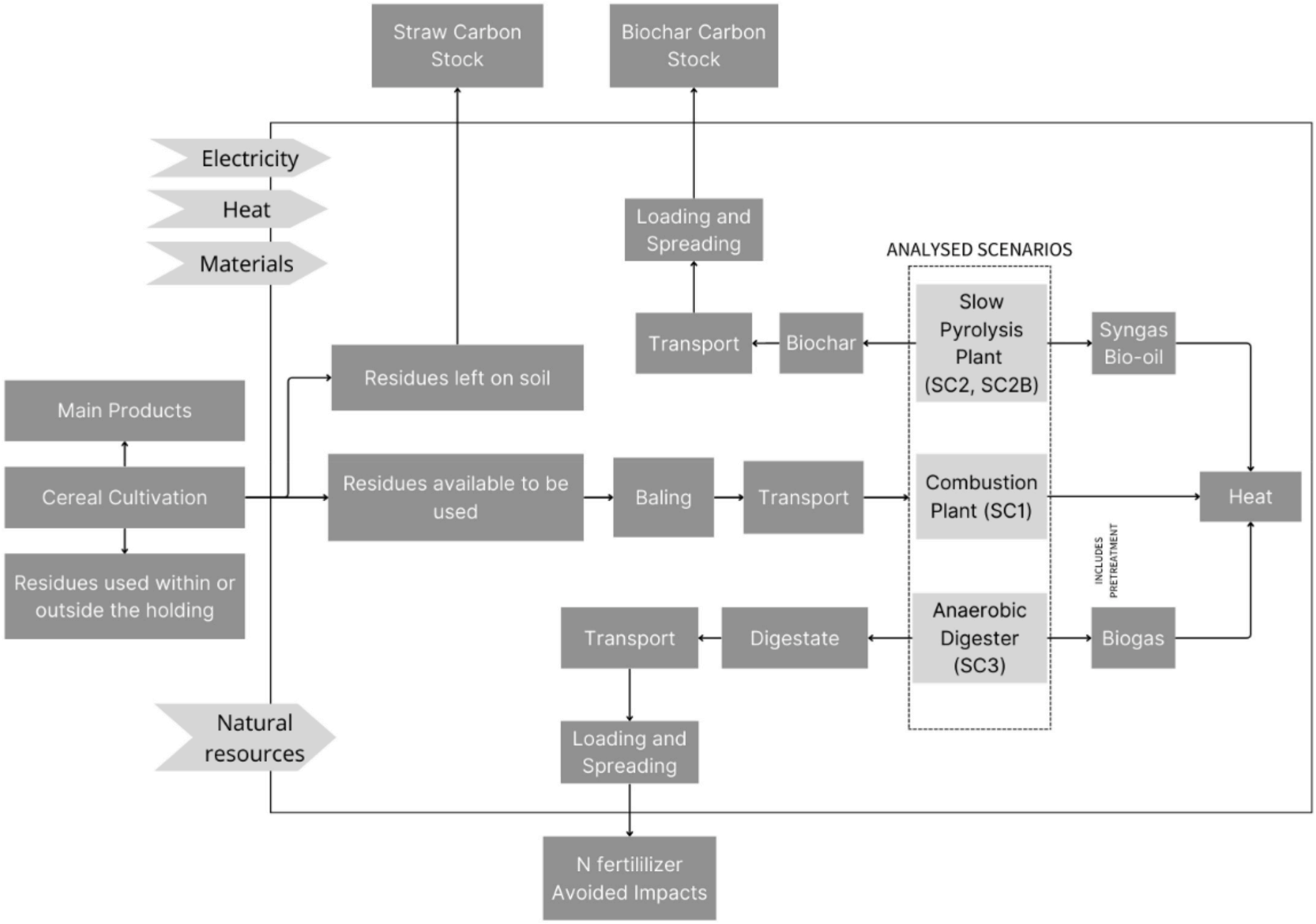

Fig. 2. System boundaries.

Table 1
Specific inventory data (input and output) relating to the energetic valorisation of residual biomasses from cereals in Italy. (D.M.: Dry Matter; SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion).

Materials and energy	Unit	Value				Source
	Related to 1 yr	SC1	SC2	SC2B	SC3	
Crop residues	ton	1.37 10^5	1.37 10^5	7.87 10^5	1.37 10^5	ISTAT (2024)
Transport (out)	tkm out	1.37 10^7	1.37 10^7	7.87 10^7	1.37 10^7	(Cherubini and Ulgiati, 2010)A
Transport (in)	tkm in	–	4.74 10^6	2.72 10^7	9.32 10^6	Cherubini and Ulgiati (2010)
Water	m^3	–	–	–	3.06 10^5	Alengebawy et al. (2022)
Electricity digestion	kWh	–	–	–	1.66 10^7	Alengebawy et al. (2022)
Electricity plant (including pretreatment)	kWh	7.96 10^6	3.01 10^6	1.72 10^7		Ecoinvent 3.8
Electricity chopping		–	–	–	2.02 10^6	Alengebawy et al. (2022)
Electricity separation	kWh	–	–	–	2.02 10^7	Cathcart et al. (2023)
Heat	kWh	–	–	–	2.96 10^7	Alengebawy et al. (2022)
NaOH	kg	–	–	–	1.21 10^6	Alengebawy et al. (2022)
Produced biochar	ton	–	4.74 10^4	2.72 10^5	–	Gong and Kung (2021)
Produced syngas	ton	–	3.79 10^4	2.17 10^5	–	Gong and Kung (2021)
Produced bio-oil	m^{3}ton	–	3.32 10^4	1.90 10^5	–	Gong and Kung (2021)
Produced digestate	ton	–	–	–	9.61 10^4	Andersen et al. (2022)
Produced heat	GJ	1.59 10^6	6.01 10^5	3.45 10^6	5.46 10^5	Calculated
Biochar/Manure spreading	kg	–	4.74 10^7	2.72 10^8	9.32 10^7	Ecoinvent 3.8
Baling	kg	1.37 10^8	1.37 10^8	7.87 10^8	1.37 10^8	Ecoinvent 3.8
Other data						
Thermal efficiency of bio-oil and syngas	%	72.89				Hasan et al. (2024)
Dry matter crop residues	%	0.89				IPCC, 2006
Biochar transportation losses	%	3				Yang (2021)
Straw transportation losses	%	1				Assumption
Digestate yield	%	70				Andersen et al. (2022)
Digestate Nitrogen content	%	0.3				Nyang'au et al. (2023)

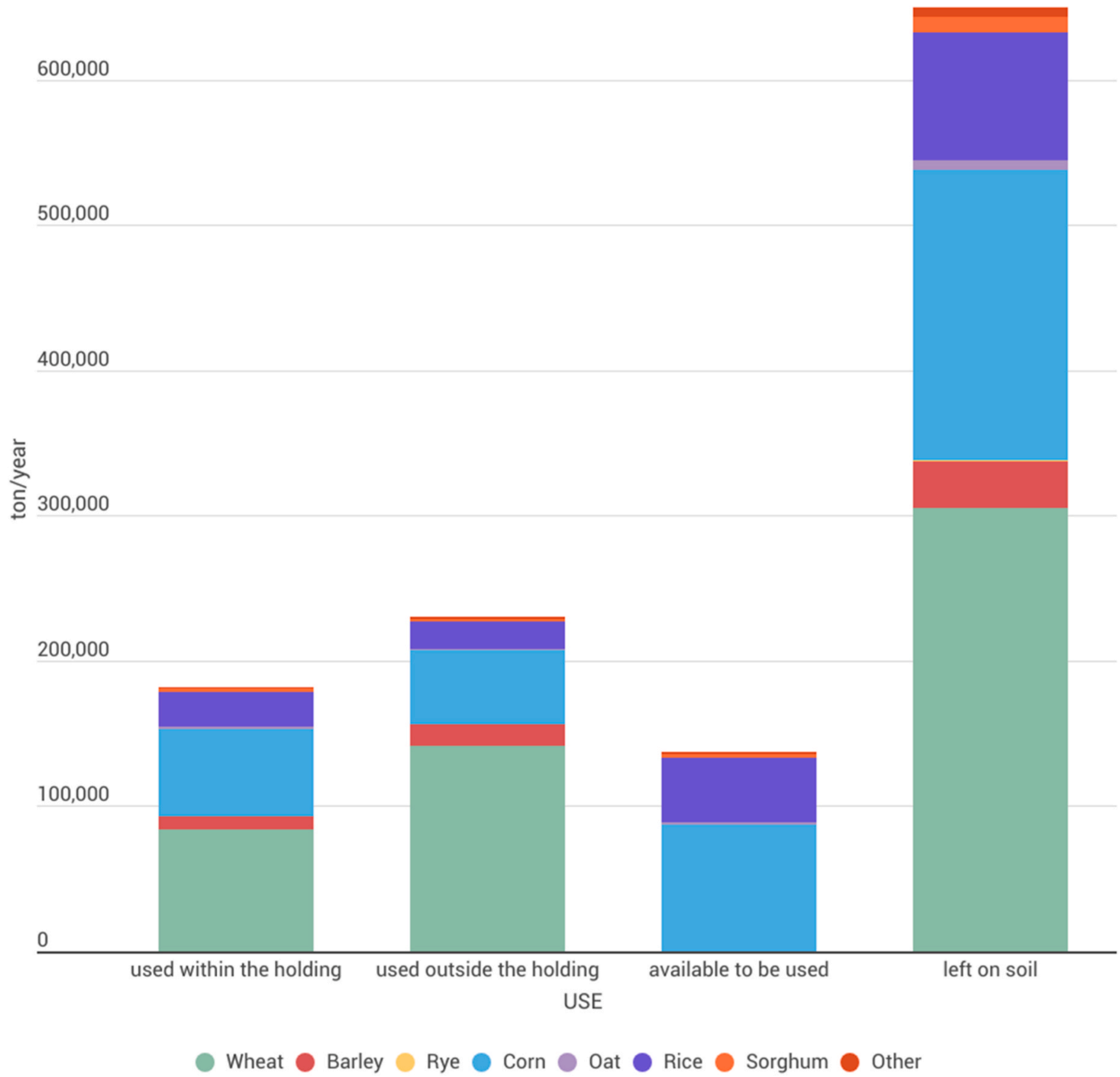

Fig. 3. – Yearly total production of losses by different uses. Authors elaboration based on ISTAT data (Femia and Manzi, 2016; ISTAT, 2024).

primary applications of side flows from cereals in Italy. It presents annual quantities obtained from data collected for the seasons 2019–2023, measured in tonnes allocated across different use categories. Furthermore, the amount sourced from each considered cereal type is outlined for each of the four identified categories. The cereals include wheat, barley, rye, corn, oats, rice, sorghum, and others. For this study, only the "left on soil" portion was considered to determine the "available to be used" fraction obtained when the residues exceeded the amount needed for soil health and could be allocated to energy valorisation scenarios. The segment labelled "available to be used" represents quantities potentially employable in subsequent valorisation processes, predominantly consisting of corn and rice residues. It is worth noting that wheat and barley residues are currently unavailable for energetic use due to their actual other extensive within and outside the holding uses and the imperative need to leave them in the soil, as prescribed by (Scarlat et al., 2010), to maintain organic matter and organic carbon and protect soil from erosion.

Table 2 shows the results of 1 GJ of heat obtained after processing the inventory data reported in Table 1. It is important to note that agriculture cultivation is not included in the system boundary, mainly because, as in other studies, the agro-residues are treated as waste streams (Yang, 2021). At the same time, capital investments were excluded. The construction of a thermo valorisation plant is an important focus. Yet, many studies have not paid attention to its analysis due to the unavailable data on infrastructure establishment and plant operation. For future large-scale equipment or integration with a power plant or bio-refinery plant (Azzi et al., 2019), including the LCA construction, operation, and maintenance phases (Yang, 2021).

SC1: in this scenario, the direct combustion of biomass "available to be used" is practised to provide thermal energy (Z. Wang et al., 2020), and this energy is considered to substitute an equivalent amount of heat produced in Italy in a combined cycle power plant, in a heat and power cogeneration plant using natural gas. The technology is commercially available and presents minimum risk to investors. The product is heat, which must be used immediately for heat and/or power generation, as storage is not viable. Since the overall conversion of biomass to electricity is variable, ranging from 15 % for small plants to 30 % for larger and newer ones, heat production has been chosen as the primary unit for analysis (Bridgwater, 2003). This ensures consistency across different plant sizes and avoids uncertainties associated with electricity generation efficiency. In nearly all impact categories, direct straw combustion with its associated energy consumption and emissions is the primary contributor to the potential impacts (see Fig. 4). In the case of Global Warming Potential (GWP), the CO_2 stored because of straw left on the

Table 2
Impact categories for all scenarios (SC1, SC2, SC2B and SC3) related to 1 GJ of heat produced. (SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion. SC1, SC2, and SC3 convert only the "available to be used" fraction, while SC2B includes the Slow Pyrolysis of all the cereal residues).

Impact category	Unit	SC1	SC2	SC2B	SC3
CLIMATE CHANGE	kg CO_2eq	$-8.73\ 10^{1}$	$-3.20\ 10^{2}$	$-1.44\ 10^{2}$	$-1.68\ 10^{2}$
OZONE DEPLETION	kg CFC11 eq	$-4.64\ 10^{-6}$	$-1.41\ 10^{-6}$	$-1.41\ 10^{-6}$	$4.78\ 10^{-6}$
IONISING RADIATION	kBq U-235 eq	$4.26\ 10^{-1}$	1.67	1.67	4.29
PHOTOCHEMICAL OZONE FORMATION	kg NMVOC eq	$-6.27\ 10^{-3}$	$3.60\ 10^{-2}$	$3.60\ 10^{-2}$	$1.48\ 10^{-1}$
PARTICULATE MATTER	disease inc.	$1.70\ 10^{-5}$	$1.79\ 10^{-5}$	$1.79\ 10^{-5}$	$1.91\ 10^{-6}$
HUMAN TOXICITY, NON-CANCER	CTUh	$1.06\ 10^{-5}$	$1.08\ 10^{-5}$	$1.08\ 10^{-5}$	$4.01\ 10^{-7}$
HUMAN TOXICITY, CANCER	CTUh	$1.97\ 10^{-8}$	$2.80\ 10^{-8}$	$2.80\ 10^{-8}$	$1.63\ 10^{-8}$
ACIDIFICATION	mol H^{+} eq	$8.42\ 10^{-2}$	$1.34\ 10^{-1}$	$1.34\ 10^{-1}$	$2.12\ 10^{-1}$
EUTROPHICATION, FRESHWATER	kg P eq	$5.91\ 10^{-4}$	$2.08\ 10^{-3}$	$2.08\ 10^{-3}$	$7.50\ 10^{-3}$
EUTROPHICATION, MARINE	kg N eq	$-2.62\ 10^{-3}$	$8.49\ 10^{-3}$	$8.49\ 10^{-3}$	$4.91\ 10^{-2}$
EUTROPHICATION, TERRESTRIAL	mol N eq	$3.34\ 10^{-3}$	$1.24\ 10^{-1}$	$1.24\ 10^{-1}$	$5.18\ 10^{-1}$
ECOTOXICITY, FRESHWATER	CTUe	$1.31\ 10^{2}$	$3.33\ 10^{2}$	$3.33\ 10^{2}$	$4.72\ 10^{2}$
LAND USE	Pt	$1.66\ 10^{1}$	$1.20\ 10^{2}$	$1.20\ 10^{2}$	$2.17\ 10^{2}$
WATER USE	m^3 depriv.	$4.75\ 10^{-1}$	1.45	1.45	$4.51\ 10^{1}$
RESOURCE USE, FOSSILS	MJ	$-3.27\ 10^{2}$	$-1.05\ 10^{2}$	$-1.05\ 10^{2}$	$3.55\ 10^{2}$
RESOURCE USE, MINERALS AND METALS	kg Sb eq	$1.11\ 10^{-5}$	$1.04\ 10^{-4}$	$1.04\ 10^{-4}$	$1.72\ 10^{-4}$

soil can offset emissions related to combustion, transportation, and baling. This has been calculated assuming that every ton of straw incorporated in the soil leads to 50 kg of carbon retained in the soil, according to Phan-Huy et al. (2023). This amount contributes to the delayed emissions corresponding to temporal carbon storage obtained using yearly averages of carbon accumulation within the system. The carbon accumulation has been approximated considering how much biogenic carbon was retained when adding new straw each year (Phan-Huy et al., 2023). The avoided impacts fully compensate for the impacts due to Photochemical Ozone Formation, Eutrophication-Marine, Resource Use-Fossil and Ozone Depletion. Additionally, the avoided impacts contribute to reducing the environmental impacts in 9 impact categories (Fig. 4). In this first scenario, the reduction in fertiliser input was not considered; besides, a ton of dried straw contains organic material and nutrients such as carbon (C = 43.1 %), nitrogen (N = 0.81 %), phosphorus (P = 0.88 %), and potassium (K = 19.1 %) in amounts (X. Wang et al., 2020); therefore, these nutrients would potentially be available in the soil if the straws were appropriately incorporated into it leading to a reduction in fertiliser use (Silalertruksa and Gheewala, 2013).

SC2: in this scenario, thermal decomposition occurs in the absence of oxygen through the pyrolysis process, utilising biomass deemed "available to be used" to generate biochar, syngas and bio-oil. Besides, some authors demonstrated that the co-pyrolysis process could have significantly better potential for enhancing product properties and expanding their applications than pyrolysis (Gusiatin, 2024; Magdziarz et al., 2024), the present study aims to study cereal residues' valorisation potential without adding other residual biomasses. Syngas and bio-oil products create heat while biochar is reintroduced into the soil. Biochar, being a carbon-rich solid material, has diverse potential applications, including soil amendment, energy substitution, adsorption, catalyst support, and CO_2 adsorption, among others (He et al., 2021a; Kant et al., 2021; Qiao and Wu, 2022). While acknowledging its additional beneficial properties for soil health, fertility enhancement, pollution reduction, and promotion of biotic populations, our focus in this study remains on assessing its contribution to carbon sequestration and climate change mitigation (He et al., 2021b). Several studies demonstrate that applying biochar significantly increases native soil organic carbon (SOC) accumulation by enhancing the proportion of native recalcitrant SOC. Moreover, biochar application has important implications for long-term agricultural soil organic carbon sequestration. For this study, 1.78 kgCO_2eq/kg of biochar is considered sequestered, according to (Ding et al., 2023; Kalu et al., 2024; Woolf et al., 2021). The pyrolysis and transportation processes emerge as the primary contributors to all impact categories, with transportation leading in 11 out of 16 categories and pyrolysis in 5 out of 16 (see Fig. 4). The CO_2 stored in both soil residues and applied biochar effectively offsets the impact of climate change, primarily attributed to the transportation process. The avoided impacts due to the thermal energy produced in the pyrolysis process contribute to mitigating all the impact categories, fully compensating Ozone Depletion and Resource Use-Fossil (Fig. 4).

SC2B: in this scenario, thermal decomposition occurs in the absence of oxygen through the pyrolysis process, utilising all the residual biomass (left on soil + available to be used), considering that biochar will return to the soil. A high proportion of renewable energy will be generated through the combustion of bio-oil and syngas, accompanied by an increased production of biochar. Similarly to SC2, the transportation and pyrolysis processes are the primary contributors to the impact categories (see Fig. 4). The CO_2 stock due to the biochar application effectively offsets the impact of climate change, primarily attributed to the transportation process. In contrast, the avoided impacts due to the thermal energy offset the impacts into the Ozone Depletion and Resource Use-Fossil impact categories.

SC3: in this scenario, anaerobic digestion is carried out on the "available to be used" portion of residual biomass following chopping and alkali pretreatment. The alkali pretreatment is necessary to release the anaerobically digestible compounds from their stable molecular network. In fact, the fermentation of straw into biogas is difficult due to its tough structure, which hinders efficient access for the bacteria responsible for degradation. To dissolve hemicellulose or to modify the lignin structure, different pre-treatments are available in the literature, classified as physical processes, biological processes, thermal processes, and chemical processes (Kainthola et al., 2019; Mothe and Polisetty, 2021). The alkali impregnation has been selected due to the high methane yield and the low-energy and heat demand; besides, steam explosion pretreatment exhibits the highest observed biodegradability (up to 93 %, according to literature). The high energy requirements constrain this last pretreatment due to the need for elevated temperatures and high pressures necessary for the process (Andersen et al., 2022; Yu et al., 2019). Additionally, anaerobic co-digestion could show synergistic effects on biogas production, yielding 20 % more than mono-digestion (Rahmani et al., 2022), but the mixing with other biomasses is beyond the goal of the present paper.

The resulting biogas is utilised for heat generation, while the digestate derived from organic matter feedstock retains the remaining nutrients from the digested material and acts as a soil amendment, showing crop yield enhancement comparable with those achieved using mineral fertilizers, and therefore, can primarily substitute the need for nitrogen-based inorganic fertilisers (Möller, 2015). Once again, the contributions from transportation and anaerobic digestion, including biogas combustion for heat production, dominate the process contribution to all the impact categories (see Fig. 4). The CO_2 stored from straw left on the soil can partially offset emissions associated with transport and heat production in the climate change impact category. The avoided impacts from substituting nitrogen fertilisers contribute minimally to the impact categories under analysis (van Midden et al., 2023). Additional benefits

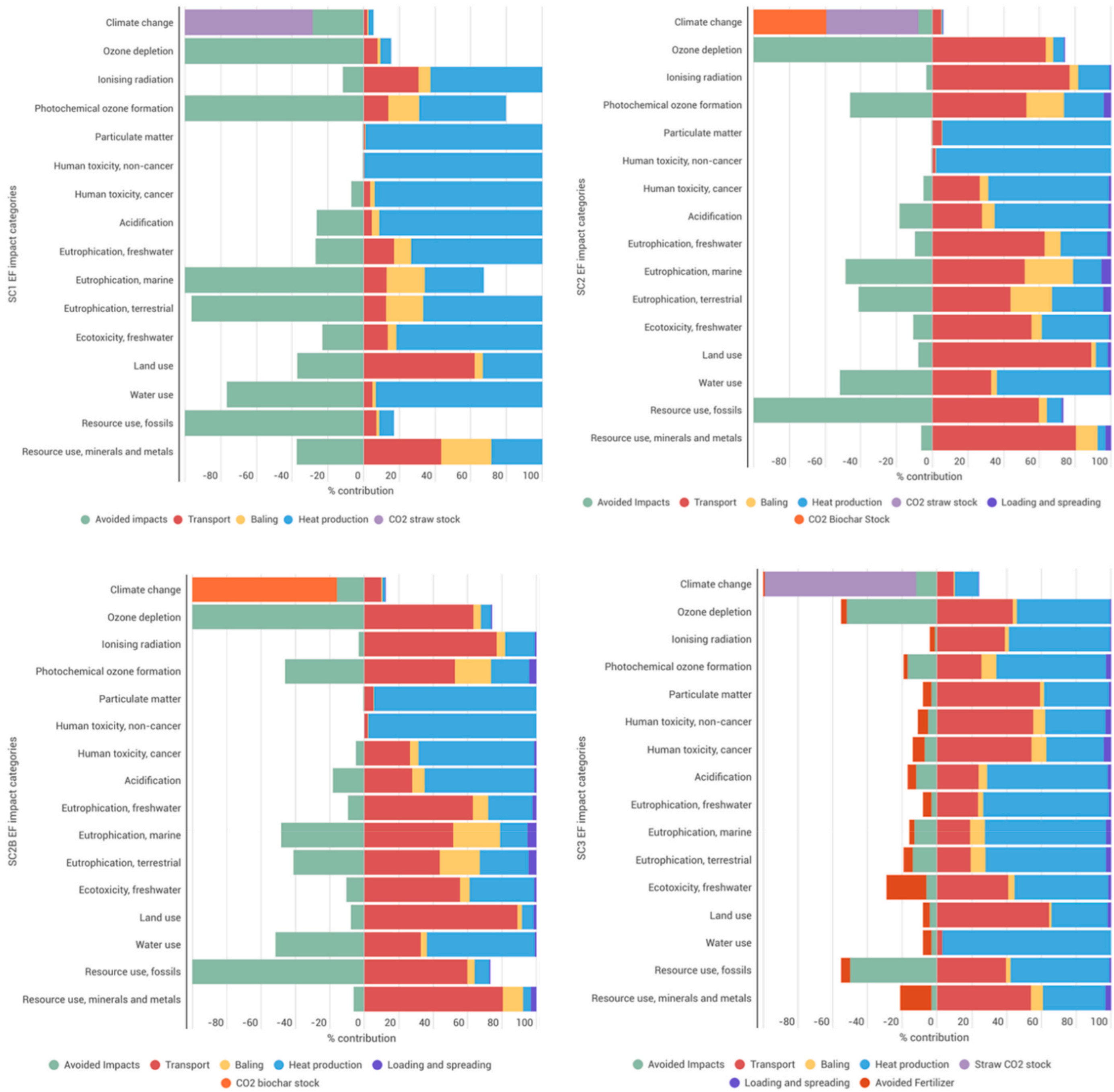

Fig. 4. Scenarios impact categories contributions. (SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion. SC1, SC2, and SC3 convert only the "available to be used" fraction, while SC2B includes the Slow Pyrolysis of all the cereal residues).

from digestate application have not been included in the study. Adding anaerobic digestate to soil has varying effects on soil biota: the solid fraction benefits soil microorganisms. In contrast, the liquid fraction slightly supports bacteria but harms mycorrhizal and saprophytic fungi. Due to the lack of carbon, ammonia toxicity, contaminants, and changes in soil pH, the whole digestate negatively affects surface-dwelling springtails, nematodes, and earthworms. However, impacts are less severe for deeper soil organisms. Biogas production should optimise digestate quality for fertiliser use without harming biogas output. Plant operators can separate or enhance digestate with materials like biochar or stabilise it through composting to improve nutrient retention and reduce environmental impacts (van Midden et al., 2023).

Fig. 5 illustrates the normalised and weighted results for scenarios SC1, SC2, SC2B, and SC3 related to producing 1 GJ of energy. SC2 emerges as the most promising option; SC2B, despite boasting higher energy production and greater biochar yields, does not rank as the optimal choice. This is attributed to the benefits achieved by failing to offset the increased direct emissions resulting from the transportation of larger straw quantities and the pyrolysis of larger volumes, coupled with the subsequent transport and spreading of significant amounts of biochar.

Consequently, alternative scenarios were developed, reducing the distance to 10 km (short transport: ST) and favouring fast pyrolysis to maximise energy production over biochar yield (low biochar: LB), as reported in Table 3. It is evident from the results that the most favourable outcome is associated with the scenario characterised by slow

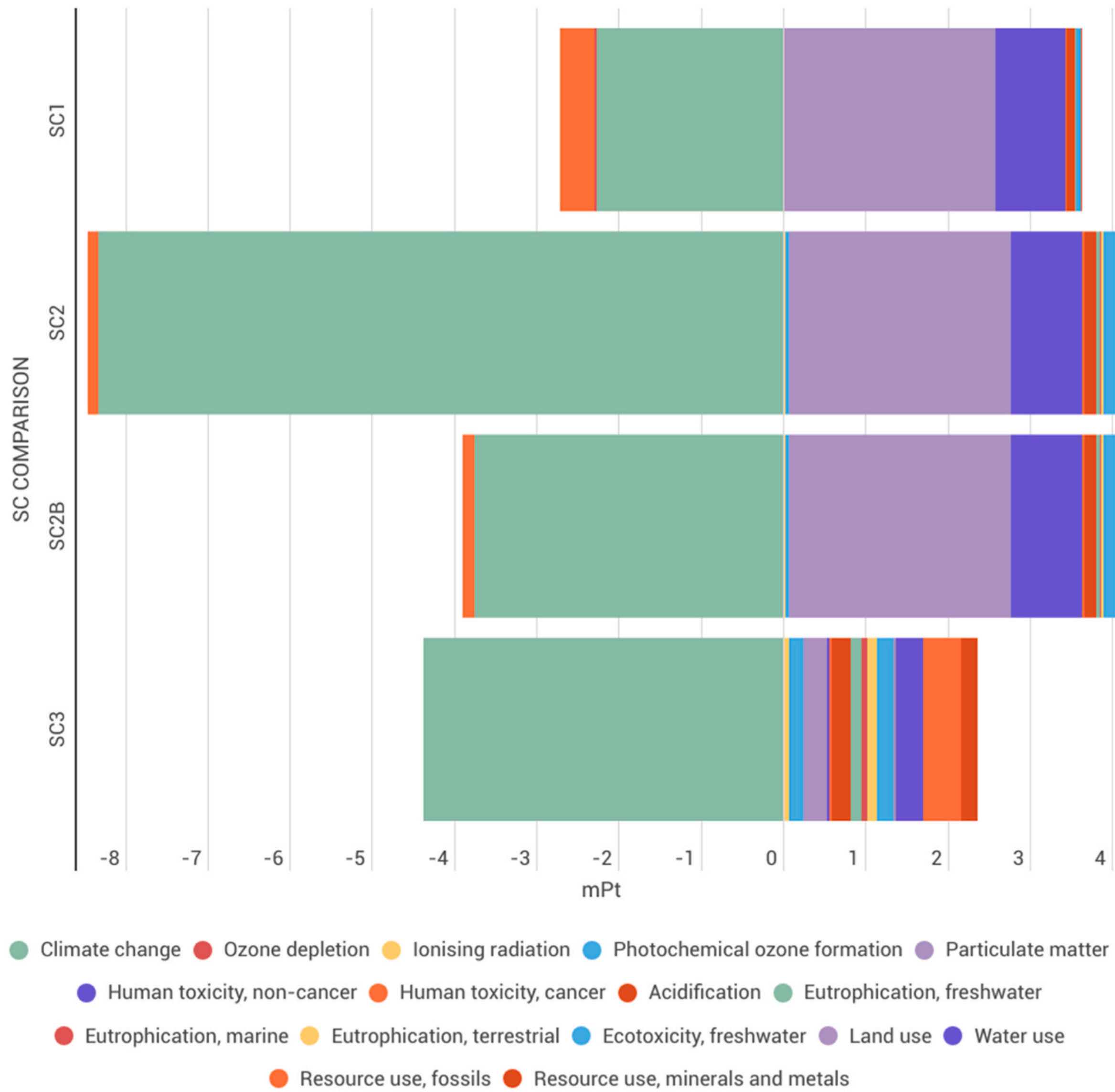

Fig. 5. Normalised and weighted results for scenarios SC1, SC2, SC2B, and SC3 related to producing 1 GJ of energy. (SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion. SC1, SC2, and SC3 convert only the “available to be used” fraction, while SC2B includes the Slow Pyrolysis of all the cereal residues).

Table 3
Impact categories relative variations for SC2 LB (low biochar) and SC2 ST (short transport) compared to SC2 related to 1 GJ of heat produced.

Impact category	Unit	SC2 LB	SC2 ST
CLIMATE CHANGE	kg CO2 eq	−62 %	4 %
OZONE DEPLETION	kg CFC11 eq	157 %	220 %
IONISING RADIATION	kBq U-235 eq	−51 %	−71 %
PHOTOCHEMICAL OZONE FORMATION	kg NMVOC eq	−85 %	−88 %
PARTICULATE MATTER	disease inc.	−3 %	−5 %
HUMAN TOXICITY, NON-CANCER	CTUh	−1 %	−2 %
HUMAN TOXICITY, CANCER	CTUh	−20 %	−25 %
ACIDIFICATION	mol H^+ eq	−26 %	−31 %
EUTROPHICATION, FRESHWATER	kg P eq	−49 %	−62 %
EUTROPHICATION, MARINE	kg N eq	−95 %	−90 %
EUTROPHICATION, TERRESTRIAL	mol N eq	−71 %	−67 %
ECOTOXICITY, FRESHWATER	CTUe	−42 %	−56 %
LAND USE	Pt	−61 %	−87 %
WATER USE	m^3 depriv.	−46 %	−61 %
RESOURCE USE, FOSSILS	MJ	145 %	200 %
RESOURCE USE, MINERALS AND METALS	kg Sb eq	−60 %	−77 %

pyrolysis of the “available to be used” portion of the residual biomass at a shorter distance (SC2 ST). Sensitivity Analysis reveals the importance of each factor in determining the total impact. The analysis shows very low correlations between input parameters, suggesting that the input parameters are independent of each other, which is suitable for the reliability of the sensitivity analysis. Biochar stock has the highest influence (First-order index: 0.5783 ± 0.0584). Transport has a minor influence (First-order index: 0.0899 ± 0.0229), while baling, loading and spreading biochar has negligible influence.

This research underlines that the biochar yield (12–40 %) affecting the amount of biochar that will be obtained is one of the most critical uncertainties. This parameter is aligned with the finding of Yang (, which demonstrated that all of the parameters (biochar yield, biochar carbon content, and electricity conversion efficiency of bio-oil and syngas) directly influence environmental performance. The uncertainty of transportation distance could affect the environmental benefits of biochar production, as underlined by Lu and Hanandeh (2019) and Yang et al. (2020) and as demonstrated by the reduction obtained by shifting to the ST scenarios. However, these reductions had a minimal effect on total GHG emissions, with the short distance scenario (SC2 ST) having a 4.4 % reduction in GHG emissions compared to SC2. Similar results have been obtained by Yang et al. (2016), who analysed the effect of transportation distances from 0 to 200 km and found a 2.34 % increase in GHG emissions for longer distances (Yang et al., 2016).

The climate effectiveness of using residual biomass is the combination of avoided emissions that can be achieved through material substitution and the delayed emissions achievable through temporal carbon storage. Italy was selected as a case study to define the maximum annual benefits of residual biomass pyrolysis at the national level, with results as a reference for analysing other countries' situations. The data on available temporary crop residues are presented in Fig. 3. The crop residues potentially suitable as feedstock for biochar production totalled 1.37×10^5 tons. Consequently, the annual carbon sequestration potential of biochar produced via slow pyrolysis of these residues was estimated at approximately 8.33×10^4 tons of CO_2 (see Fig. 6), to be added to the CO_2 stock obtained from residual biomasses left on soil, contributing to $1{,}06 \times 10^5$ tons CO_2. Additionally, 1.14×10^6 GJ of heat can be produced, saving the emissions of 2.91×10^4 tons of CO_2eq, equivalent to the amount produced by a combined cycle power plant using natural gas. The climate effectiveness of the SC2B is higher due to the increase in heat production through pyrolysis (6.51×10^6 GJ), giving 1.67×10^5 tons of avoided emissions to be added to 4.77×10^5 tons of delayed emissions from biochar application. The primary contributors to these potentials were rice and corn residues for biochar because they constitute the central residues of the "available to be used" fraction, while wheat, corn and rice are for the residual biomasses left on the soil.

Considering an energy efficiency of 33 % and 35 % (Yang, 2021) for converting heat into energy for bio-oil and syngas, respectively, it is possible to calculate the share of renewable energy in Italy from the pyrolysis of avoidable cereal residual. According to an IEA report, Italy generated 38 % of its domestic energy production from biofuels and waste in 2022 (International Energy Agency, 2024a,b). Although the pyrolysis of residues may result in an inability to meet Italy's energy needs, it represents a form of energy production associated with harmful GHG emissions.

The climate effectiveness at the European level has been the subject of a study by Phan-Huy et al. (2023). In this study, the use of straw as an insulation material, combining delayed and avoided emissions, showed the highest climate effectiveness with the saving of 1344 kg CO_2eq/ton of straw, followed by using biomass to produce energy, resulting in a saving of 930 kg CO_2eq/ton of straw. In the latter case, only avoided emissions were estimated, and biochar was not included as a carbon

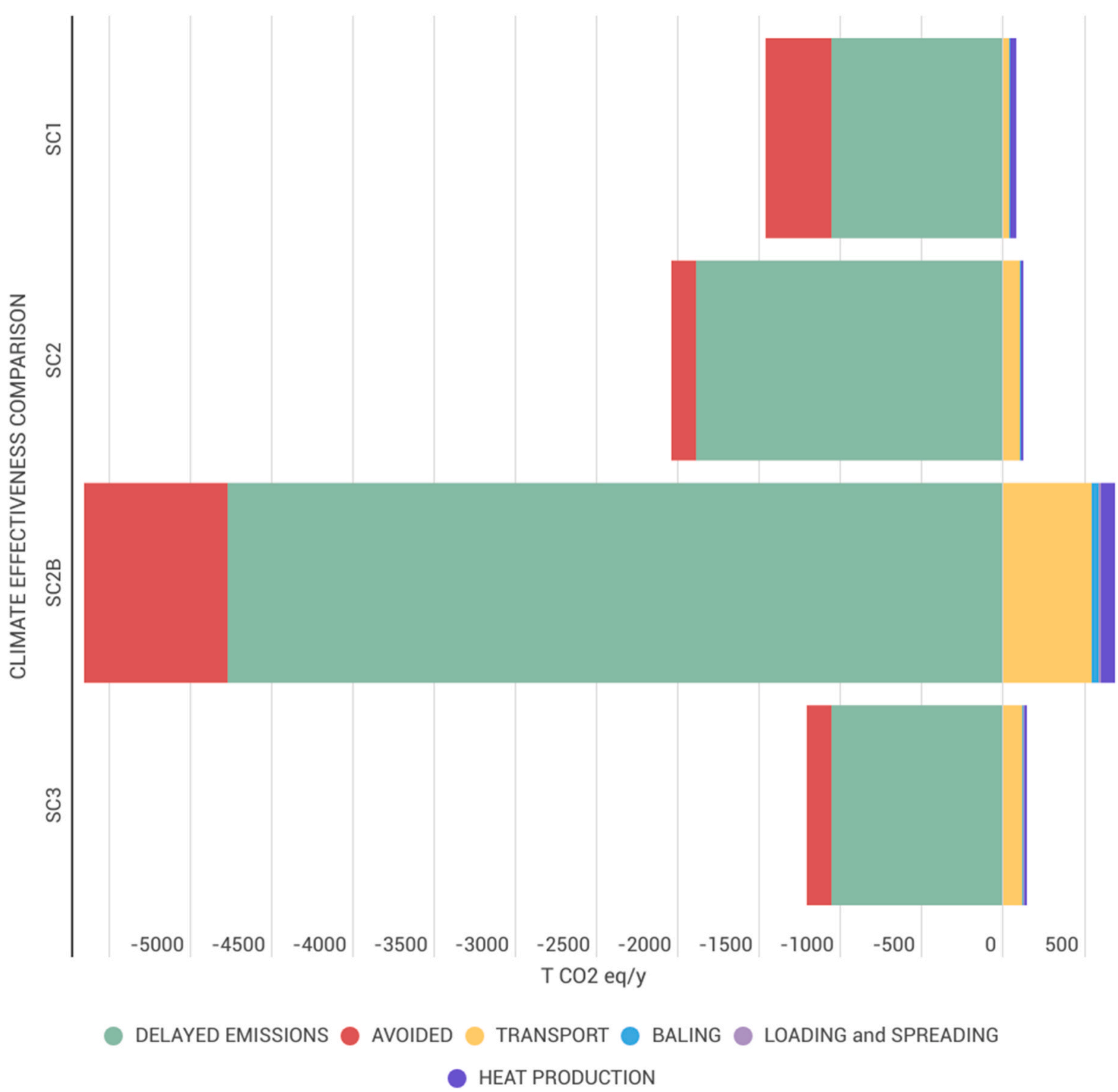

Fig. 6. – Climate effectiveness of all scenarios compared. (SC1: Combustion; SC2: Slow Pyrolysis; SC3: Anaerobic digestion. SC1, SC2, and SC3 convert only the "available to be used" fraction, while SC2B includes the Slow Pyrolysis of all the cereal residues).

storage option. The climate effectiveness per ton of straw in the current study is higher because both avoided and delayed emissions from straw left on soil and biochar returned to the soil have been considered. These amount to a total of 3635 kg CO_2eq/ton of straw. Phan-Huy et al. (2023) also estimated emissions of 8 kg CO_2eq to produce 1 GJ, while our estimations give emissions of 4.56 and 20.2 kg of CO_2eq released, respectively, in scenarios SC1 and SC2. Röder et al. (2024) instead estimated 131.6 kg CO_2eq to produce 1 GJ, while our estimations give emissions of 53.3 kg of CO_2eq released for SC3. Delayed emissions compensate entirely for these emissions, and an additional benefit is obtained by considering also avoided emissions. Alengebawy et al. (2022) made a similar estimation considering the energetic valorisation of rice straw in China using syngas, briquette fuel, and biogas. Two of the three scenarios are identical to the SC2 and SC3 of the current study, and they also showed net negative values of GHG emissions. The net reduced GHG emissions were the highest in the syngas scenario (2315 kg CO_2eq/ton of straw). They were lower than 1500 kg CO_2eq/ton of straw and almost similar in briquette fuel and biogas scenarios. Even though the results are similar to those in the present study, the reductions observed in Alengebawy et al. (2022) are attributed to the beneficial credits from biofuel production scenarios that replace the open-field burning of rice straw, which contributes 1469 kg CO2eq, rather than to delayed emissions. Open burning of straw is a common practice in rice straw management in Asia, significantly contributing to air pollution by releasing large amounts of organic and inorganic macro and micro-pollutants into the atmosphere (Paris et al., 2023). Bressan et al. (2022) considered three scenarios: the collection and baling of rice straw (CB), the well-established practices of open field burning (OFB) and soil incorporation (SI). CB is intended for subsequent use of biomass for energy production, and avoided emissions have been estimated considering that if the straws are not used to produce energy, the energy supply will take place using traditional energy sources. They found that collecting and baling rice straw decreases by 96 % particulate matter production, 60 % carbon dioxide emissions, and 40 % acidification compared to the actual rice straw management in Novara province, including soil incorporation and open field burning. It's important to note that delayed emissions are not included in this assessment. Furthermore, this study focuses on the agricultural phase within the system boundaries without considering straw as a byproduct. Additionally, this same study lacks detailed definitions of the energy valorisation processes, which are based solely on the energetic potential of straw obtained from Low Heating Value (LHV) and without considering the amount that must be left on soil for sustainable agronomic purposes. In any case, it is suggestive that the manuscript provides the same conclusion, that straw can contribute to renewable energy at the local and/or national levels.

LCA plays a vital role in evaluating the environmental impact of alternative crop residue uses. Expanding the analysis beyond GHG emissions is crucial for a truly comprehensive understanding of sustainability. This necessitates incorporating a broader spectrum of environmental factors and economic and social considerations. While GHG emissions are critical, focusing solely on them provides an incomplete picture. Even though the LCA analysis was conducted considering numerous impact categories, some aspects are not accounted for. Among these, soil health, for example, plays a fundamental role in maintaining diverse ecosystem services, with carbon storage being just one facet. It's essential to consider potential trade-offs associated with different crop residue utilisation methods. Biochar application, for instance, exemplifies an approach that acknowledges the importance of various environmental factors, including biomass production, environmental protection (beyond solely climate change), gene preservation within the soil, support for human activities, raw material sourcing, and its significance in terms of geogenic and cultural heritage (Yang, 2021). Ding et al. (2017) reported that biochar offers indirect and direct benefits for soil remediation. Indirectly, it improves soil properties by enhancing adsorption, which reduces pollutant mobility and protects plants and organisms. Biochar also promotes microbial activity that degrades or transforms some organic pollutants. Additionally, biochar can directly remediate specific pollutants by binding heavy metals and reducing their bioavailability. It can also adsorb and degrade polycyclic aromatic hydrocarbons (PAHs) and pharmaceuticals. The effectiveness of biochar in this context depends on several factors, including the type of pollutant, soil properties, and biochar's characteristics. These characteristics are directly linked to the feedstock material used and the pyrolysis conditions employed during production. In their review, Nogués et al. (2023) state that biochar application holds promise for capturing carbon in Mediterranean soils vulnerable to water scarcity and organic matter loss. Analysing field trials from Italy, Spain, Portugal, and Turkey, this review reports that biochar effectively stores carbon due to its high proportion of stable carbon. It also shows that biochar improves water retention during drought and summer.

Besides the obtained results, straw valorisation processes lag other renewable energy sectors like wind and solar due to the high biomass collection costs, the competitive uses and the dispersed nature of straw production and valorisation plants (Mofijur et al., 2019). Building a sustainable straw power generation system aligns with Italy's development strategy (Candelise and Ruggieri, 2020; Faraji Abdolmaleki et al., 2023). However, a complete sustainability assessment is required before investing in the development of technology. For these reasons, a robust sustainability assessment must extend beyond environmental factors. Economic considerations like the market viability of alternative residue uses, potential job creation, and the impact on rural livelihoods are crucial (Krishna and Mkondiwa, 2023). Social factors such as equity in accessing these technologies and the potential effects on cultural practices associated with traditional residue management should also be considered. By encompassing a more comprehensive range of environmental factors, economic considerations, and social impacts, it can generate a more holistic understanding of the sustainability of alternative crop residue uses. Moreover, although each valorisation technology may prove advantageous, using residual biomasses in combination could further enhance their efficiency. The proposed widespread approach is essential for developing and implementing practices that contribute to a sustainable agricultural system, fostering environmental responsibility, economic prosperity, and social equity.

4. Conclusion

The study focused on temporary cereal crops cultivated in Italy, using average production data from 2019 to 2023, and can be considered a preliminary LCA-based eco-design of various energy valorisation methods for agro-residues from cereal production in the country. Although biomasses are often valorised together in several studies and technological applications, this paper focuses on comparing the environmental impacts and benefits of valorising only cereal residual straws. The results of this research underline that the slow pyrolysis scenarios in which biochar is returned to soil are the most promising ones regarding climate effectiveness and overall environmental impacts. Although no other benefits of biochar have been considered, the latter shows promise in achieving carbon-smart management of agro-residues within the agroecosystem, addressing climate change, and enhancing economic sustainability. Moreover, biochar application to soils offers various benefits, including improved soil quality, plant growth, disease control, and pollutant removal. However, factors such as biomass source, pyrolysis temperature, and application rate are critical to determining these effects. Thus, the role of biochar in agricultural soils remains debated, with benefits often limited to specific conditions (Kavitha et al., 2018). This is why customising pyrolysis design and selecting the appropriate technology and position of plants for biochar production is crucial for maximising environmental and financial benefits tailored to the local/regional context. Reducing the distance of the pyrolysis plant significantly helps lower the impacts more than increasing energy production. Despite the variation in results across the three studied scenarios, all exhibited more beneficial environmental performances than using natural gas to produce the same amount of heat. However, further research is needed to mitigate impacts systematically, making the bioenergy scenarios competitive with other alternatives, fostering the sustainable use of residual biomasses, and including the potential benefits of mixing different biomasses.

Although the study is focused on Italian production, it can be applied to other Mediterranean regions due to the similarities in agricultural practices. Italy has a variable orographic configuration and, consequently, a high variability of farm products. Specifically, this analysis focuses on cereal residues, as it has been shown that the highest share of bioenergy potential can be produced from agricultural residues, particularly from cereals, legumes, and potatoes, which have the highest average theoretical energy potential (Di Fraia et al., 2020). Since similar plantations characterise Mediterranean areas, the method presented in this work can be used as a starting point to assess the energy potential of residual biomass from the agro-industry of such regions.

CRediT authorship contribution statement

Diego Voccia: Writing – review & editing, Investigation, Data curation. **Sasha Abdel Sater:** Investigation. **Francesca Demichelis:** Writing – review & editing, Investigation. **Federico Froldi:** Writing – review & editing, Data curation. **Francesco Savorani:** Writing – review & editing, Investigation. **Tonia Tommasi:** Writing – review & editing, Investigation. **Somindu Wachongkum:** Writing – review & editing, Investigation. **Lucrezia Lamastra:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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