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LETTER

Climate-effective use of straw in the EU bioeconomy—comparing avoided and delayed emissions in the agricultural, energy and construction sectors

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Abstract

A transformation towards a bioeconomy is needed to reduce the environmental impacts and resource requirements of different industries. However, considering the finiteness of land and biomass, such a transition requires strategizing resource and land allocation towards activities that yield maximum environmental benefit. This paper aims to develop a resource-based comparative indicator between economic sectors to enable optimal use of biobased resources. A new methodology is proposed to analyze the climate effectiveness of using straw in the agricultural, energy and construction sectors. For this purpose, avoided and delayed emissions are analyzed for different use cases of straw and then compared. Considering only avoided emissions, the use of straw as a feedstock for bioelectricity has the highest climate effectiveness (930 kg CO_2 eq./t_{straw}). Considering only temporal carbon storage, straw-based insulation in buildings has the highest climate effectiveness (881 kg CO_2 eq./t_{straw}). Combining avoided and delayed emissions, the use of straw-based insulation has the highest climate effectiveness (1344 kg CO_2 eq./t_{straw}). Today EU-Policies incentives the use of straw in the agricultural sector and the energy sector, neglecting the benefit from its use in the construction sector. The results can support policymakers' trans-sectoral incentives, where agriculture by-products are diverted towards the use of biomass that most boost economic activities and trigger maximum environmental benefit, given the local circumstances.

1. Introduction

1.1. The vision of a European bioeconomy

To stay within planetary boundaries, industries need to transform: away from materials and processes with high-environmental impact, towards a bio-based and circular economy powered by renewable energy, i.e. a transition towards a bioeconomy. In fact, nature-based solutions for carbon uptake are required to reach carbon neutrality. Yet, there are multiple challenges related to the transition towards a bioeconomy. This includes the finiteness of land and resources available (Haberl and Erb 2017), and lacking coherence between many different policy domains since the sourcing and use of biomass can influence different economic sectors (Muscat *et al* 2021). A report on resource efficiency and climate change by the International Resource Panel of the United Nations (IRP 2020) highlights the need for policy instruments that guide the efficient use of resources to minimize the impact of material use on the climate.

The European Union (EU) wants to promote using agricultural residues, such as straw, as a feedstock for the bioeconomy to avoid competition for arable land (DG for Research and Innovation of the EC 2018). Straw is the primary agricultural residue and accounts for ca. 20% of total biomass produced in the EU (Scarlat *et al* 2019). With rising demand for biomass from different sectors, however, possible (regional) scarcity could lead to rivalry over the same resource (Daioglou *et al* 2016). Using biogenic resources not only offers an opportunity to mitigate climate change but also provides additional environmental and social benefits (Babí Almenar *et al* 2021). Due to the absence of standardized pricing for greenhouse gas (GHG) emissions and ecosystem services, there is a risk that resources will be allocated solely based on economic factors, without considering externalities (Haberl *et al* 2014).

Current frameworks on resource efficiency focus on minimizing the environmental impact of materials. Increasing material efficiency thus should reduce adverse environmental impacts caused by the extraction or use of materials (IRP 2020). This definition, however, is more relevant for non-renewable resources such as iron, cement or plastic, the use of which is associated with high life cycle emissions. In contrast, biogenic resources and their cultivation, as long as sustainably managed, can positively affect the climate, as shown for increased biomass carbon pools related to afforestation (Chen *et al* 2023) or increased soil carbon sequestration related to certain cropping systems (Valkama *et al* 2020). Even when storage is only temporary, these delayed emissions allow for lowering the temperature peak in climate scenarios and could thus help avoid some climate tipping points (Matthews *et al* 2022). Consequently, policymakers should shift the focus towards maximizing the benefits instead of minimizing impacts. Another limitation of current frameworks on resource efficiency, if applied to biogenic resources, is that the focus is on the end-use rather than the resource itself. This means that resource efficiency minimizes the impact of a particular product or service by using less or different materials. However, when considering the finiteness of available biomass, the more relevant question is: where is the biomass best allocated to maximize its benefits? In other words, there is a need to identify the effectiveness, i.e., benefits per unit of biomass, of different ways to use the same biomass to formulate policies that ensure allocation towards highly effective uses in climate-change mitigation. Such an approach aligns more with industrial ecology methods that address waste allocation between industrial sectors, rather than focusing solely on process efficiency, which aims to minimize resource consumption per production unit.

1.2. Existing straw uses in different sectors

Figure 1 shows the total availability of straw in the EU. Circa 42–63 Mt/year of straw are available considering technical harvest feasibility, sustainable removal rate and existing uses. More information on the analysis of straw availability in the EU can be found in Göswein *et al* (2021a).

1.2.1. Agricultural sector

In the agricultural sector, harvested straw is mainly used for animal bedding (Kaltschmitt *et al* 2016, Einarsson and Persson 2017). The amount of straw used for livestock in the EU is estimated to be 17.5 Mt/year (Einarsson and Persson 2017) to 28 Mt/year (Scarlat *et al* 2010). Non-used straw is often burned on the field despite being illegal (Ortiz *et al* 2008, Song *et al* 2016). The practice leads to GHG emissions (Pereira *et al* 2019). Yet, farmers use it for pest and disease control, stating that it is also the cheapest and fastest practice (Giannoccaro *et al* 2017). In contrast, straw incorporation in the soil leads to soil organic carbon accumulation and soil fertilization. It is, therefore, currently promoted by policy: at the European level through the EU's Common Agricultural Policy and at the national level through agri-environmental schemes that provide monetary incentives for farmers to leave straw on the fields, i.e. in Italy (Giannoccaro *et al* 2017) and in Ireland (IFA 2021).

1.2.2. Energy sector

The EU's share of renewable energy is increasing (Eurostat 2022). So far, the primary renewable energy source is bioenergy, for which most feedstock is provided by forestry (Scarlat *et al* 2019). To achieve the EU's ambitious renewable energy target of 40% in the energy mix by 2030, energy from biomass, including agricultural residues, will play a key role (Scarlat *et al* 2019). It is estimated that energy derived from agricultural residue can cover 2.3% to 4% of the EU's final energy consumption. In 2019, straw accounted for 75% of the agricultural residues (Scarlat *et al* 2019).

Straw is available for different end uses in the energy sector, depending on how it is processed. It can be used in its raw state or processed into straw pellets. The latter facilitates transportation thanks to a higher energy density. Straw used as solid fuels or in the form of biogas (biomass fuel) can produce electricity or useful heat, or both if used in combined heat and power plants. Further, straw can be used as feedstock for transport biofuels such as (straw) ethanol and different synthetic fuels. Today, mainly dedicated energy crops are used as feedstock for transport biofuel production in the EU: maize is the primary feedstock for ethanol, followed by sugar beet, wheat, and other cereals (European Commission 2020). However, as the subsidies shift from dedicated energy crops to residues (Einarsson and Persson 2017), straw will become a more critical feedstock because the high lignin content of straw makes it 'highly suitable' for bioethanol production (Iqbal *et al* 2016). According to the EU agricultural outlook (European Commission 2020), waste and

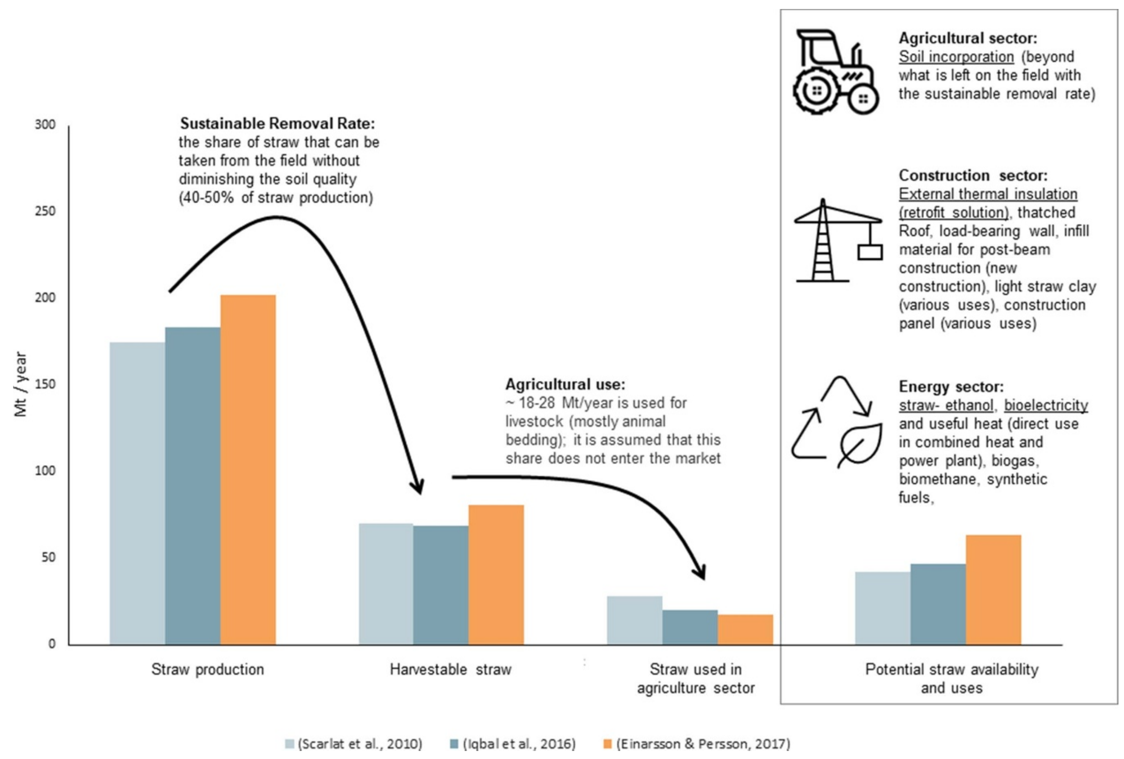

Figure 1. Straw availability in the EU based on different studies.
Notes: Values are taken from Einarsson and Persson (2017), Iqbal et al (2016), and Scarlat et al (2010). Only straw from wheat, barley, rye and oats are considered, in the EU-27 (2010 composition), to ensure comparability between studies. The underlined straw uses in the right box are analyzed in this study.

residues are the only feedstock for bioethanol predicted to grow in this decade (10.8% annual growth between 2020 and 2030).

1.2.3. Construction sector

Straw, a traditional construction material, while historically significant, currently holds modest prominence in the construction sector (FNR 2017). Yet, similar to other rising natural materials (Hoxha *et al* 2020), straw is garnering increased attention. Recent studies explore its properties—thermal insulation, acoustics, load-bearing, and fire resistance (Beck *et al* 2004, Cantor and Manea 2015, Cascone *et al* 2019). Climate advantages in construction, encompassing emission avoidance (Ben-Alon *et al* 2019, 2021) and delay (Pittau *et al* 2018, 2019, Göswein *et al* 2021b), are also researched. There are no official statistics of how much straw is used in construction today. Current straw use in construction lacks official statistics. The European Straw Building Association curates a repository of 10 000+ straw projects, reflecting its budding popularity, with France spearheading progress, erecting 500 new straw structures annually. Notably, compared to the 350 000 yearly new builds, this highlights straw construction's substantial growth potential.

Straw's forms include bales (directly shaped by harvesters) or loose (swaths). Bales find application as load-bearing walls, external insulation, or infill for frames or post-beam structures, requiring minimal processing. Most common is using bales as infill without special permits, thanks to standardized support (SRB 2019). Loose straw requires prior processing, such as bundling for thatched roofs, or conversion into cob, straw chips, and light clay straw. Straw chips, aiding insulation and retrofitting, necessitate a frame structure as mounting, also filling gaps (due to wall unevenness) for enhanced thermal insulation.

1.3. Objective of the paper

There are two ways to reduce GHG emissions through increased efficiency: one involves replacing materials with a higher environmental impact to avoid emissions, while the other entails acting as a temporary carbon sink in natural systems like soils or in artificial systems such as buildings, thereby delaying GHG emissions. Various studies have demonstrated how the use of straw can reduce GHG emissions in a specific sector: through agroecosystems and soil incorporation for carbon sequestration (Powlson *et al* 2008, Cook *et al* 2013, Lugato *et al* 2018), through production of straw-derived bioenergy and biofuels (Scarlat *et al* 2010, Sastre *et al* 2015, Pereira *et al* 2019), and through straw-derived biochar for carbon sequestration (Wang *et al* 2020). Moreover, in buildings, through straw bale construction (Chaussinand *et al* 2015), or retrofit using a timber frame with strawchips-infill (Göswein et al 2021b). And comparing straw and other fast-growing bio-based insulation materials, highlighting the full carbon capture by crop regrowth one year after construction (Pittau et al 2018). However, to our knowledge, no previous study has standardized the comparison of climate-relevant straw uses across different sectors. Most studies neglect straw's potential as a construction material for insulation, limiting its application to agriculture and energy.

This paper develops a new methodology to compare the potential climate benefits of different straw uses. We consider positive effects on the climate through avoided GHG emissions linked with material substitution or delayed GHG emissions related to temporal carbon storage in the agricultural, energy and construction sector. This paper adds to the existing body of research by providing a method of comparing these benefits, thereby supporting policymakers to reframe existing legislation or to create regulatory frameworks to incentivize straw use that maximizes its climate mitigation effects.

2. Methods and data

This study develops and applies a resource-based comparative indicator, the climate effectiveness of straw use [kg CO_{2eq}/t_{straw}]. The conceptual framework for determining climate effectiveness of different straw uses is shown in figure 2. The climate effectiveness of straw use in three sectors is compared in terms of avoided and delayed emissions for the following four use cases:

- In the agricultural sector: (1) active straw incorporation in the soil,
- In the energy sector: (2a) straw used for electricity generation (biomass fuel), and (2b) straw-based transport fuel (biofuel),
- In the construction sector: (3) retrofit system with straw chips insulation for external walls of existing buildings. For more details about this retrofit system, please refer to supplementary information (SI) I.

In the first step, we compared total life cycle emissions of selected straw uses with non-renewable alternatives using life cycle assessment (LCA). LCA assessed environmental impact over the full life cycle (Hellweg and Canals 2014). We defined functional units (FUs) for avoided emissions per use case:

$$FU_{2a,electricity} = 1 \text{ GJ from biomass fuels for electricity;}$$
$$FU_{2b,transport} = 1 \text{ GJ from biofuel for transport;}$$
$$FU_{3,construction} = 1 \text{ m}^2 \text{of retrofitted wall.}$$

Note that for agricultural use case (1), significant avoided emissions were not considered (see SI II). Avoided emissions calculations adhere to renewable energy directive (RED) II, which assigns emissions to FFCs using the EU fossil energy mix. RED II lacks details on the methodology for calculating FFC's life cycle emissions. Kalt et al (2020) stressed precise fossil fuel modeling for a thorough grasp of emissions reductions attained by shifting to renewables.

In the second step, we determined delayed emissions through temporal carbon storage using yearly averages of carbon accumulation within the system. We simplified carbon accumulation as an approximation of annual storage, considering how much biogenic carbon was retained when adding new straw each year (see figure 3). Fluxes between carbon pools are part of the carbon cycle, whereas accumulation constitutes temporal carbon storage. This storage increases the time lag between atmospheric fluxes, temporarily reducing carbon (CO_2 or CH_4) in the atmospheric carbon pool. Temporal carbon storage differs from technical carbon capture and storage (CCS), where CO_2 is compressed and stored in geological formations for centuries.

In this study, we assumed a 40% carbon content, equivalent to 0.4 kg C per kg of biomass, and evaluated each system's carbon retention capacity. The annual carbon accumulation rate represents the percentage of straw, by weight, retained as carbon when an equal amount is added annually.

For the FU for comparing delayed emissions in agricultural and construction cases (1) and (3), we used:

$$FU_{CarbonStorage} = 1 \text{ metric ton of straw.}$$

Note that no carbon storage is considered for energy use cases (2a and 2b) as we assume immediate utilization.

In the third step, we defined a functional unit for climate effectiveness as [kg CO_2 eq./t_{straw}/100 y] enabling comparability across straw uses while considering both avoided and delayed emissions.

3. Results

3.1. Material substitution impacts

We assessed avoided emissions by comparing the full life cycle emissions of specific straw uses to non-biobased, non-renewable alternatives. Figure 4 displays avoided emissions in the energy and construction sectors, including conventional material options. In the agricultural sector, straw incorporation could not replace any material or process, resulting in no avoided emissions.

For the use in the energy sector, the data is taken from the RED II (EC 2018), specifically for a transport distance of the raw material (A2) <500 km (as this distance is assumed economically and environmentally viable) for the biomass fuels, and is used to calculate avoided emissions, i.e. substituting renewables for its fossil fuel comparators (FFCs). Conventional

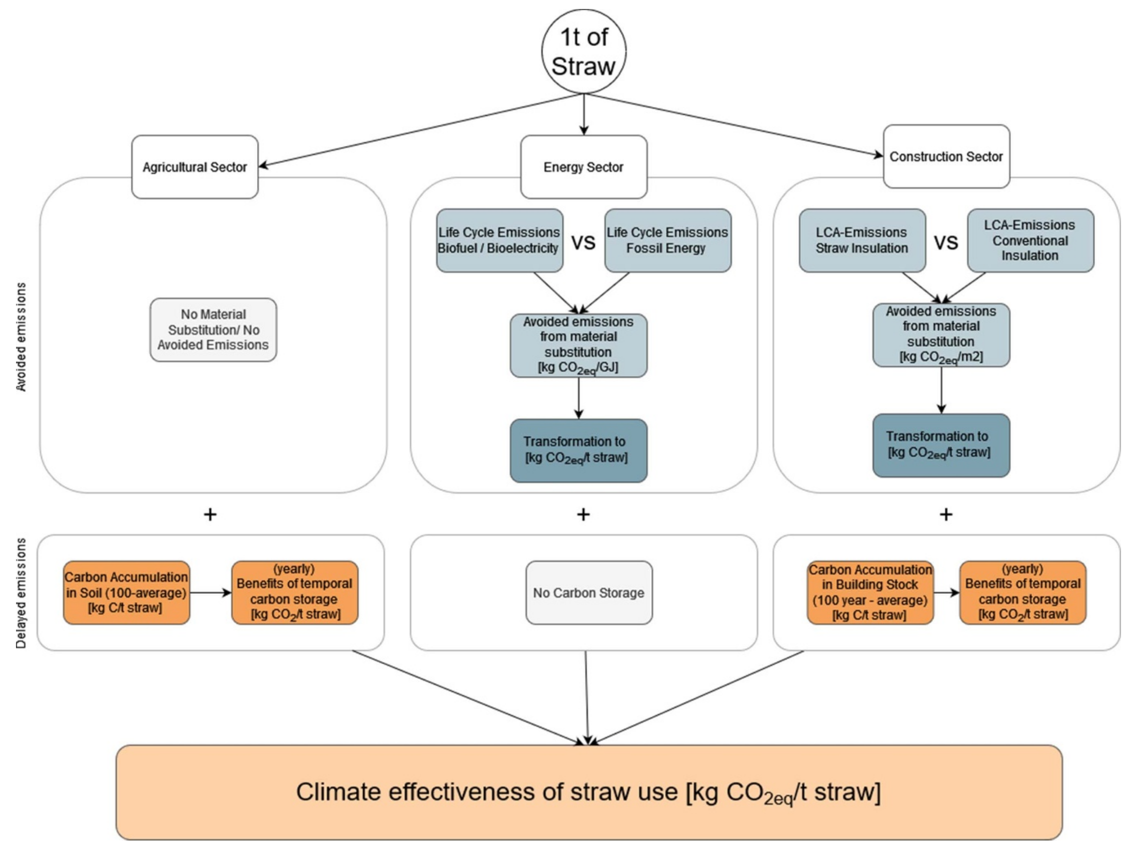

Figure 2. Conceptual framework for determining the climate effectiveness of different straw uses.

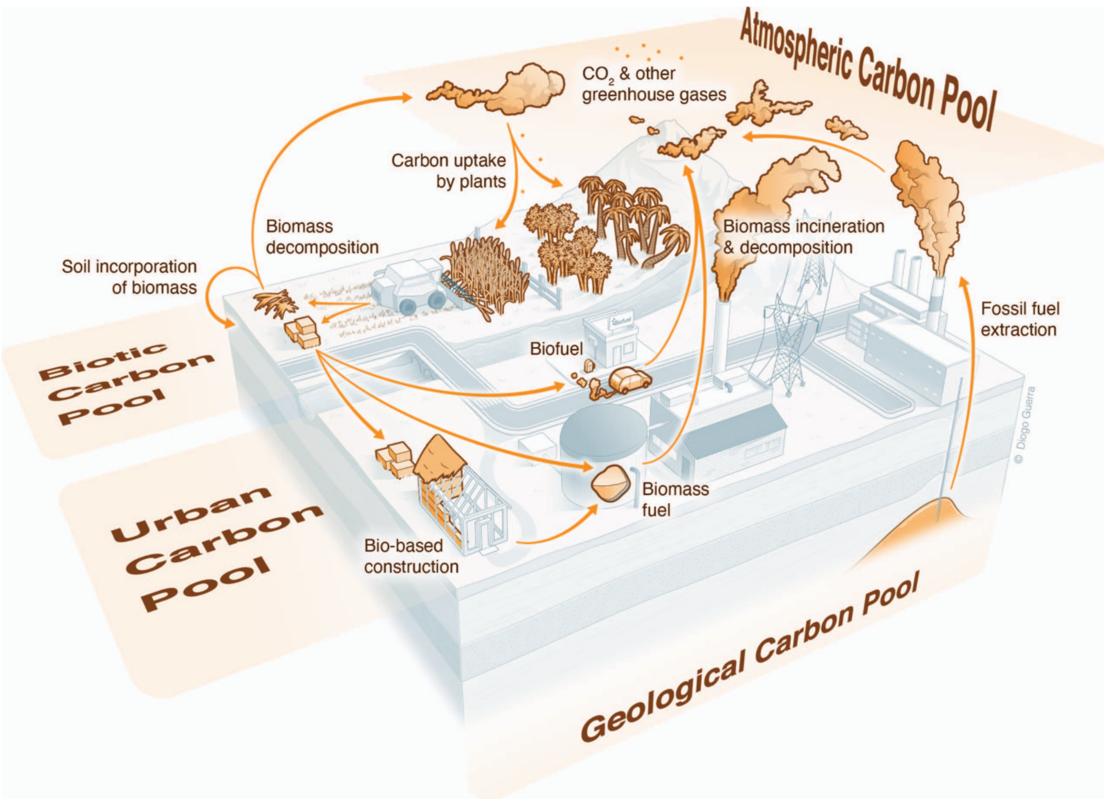

Figure 3. Schematic illustration of carbon flows and carbon pools. © Diogo Guerra. 2023.

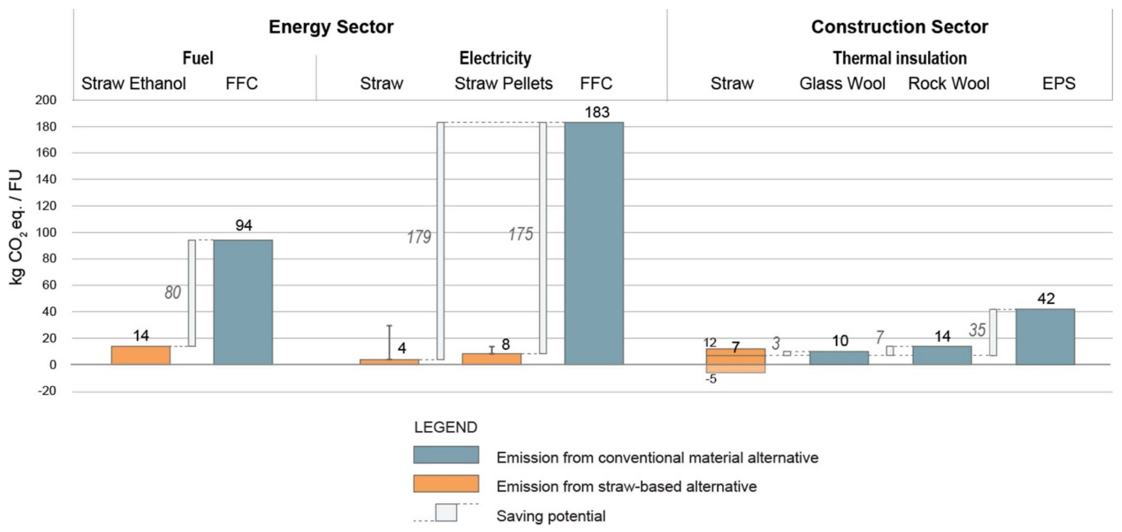

Figure 4. Avoided emissions in the energy sector and construction sector. *Note:* 'FFCs' stands for fossil fuel comparators; 'FU' stands for functional unit: in [GJ] for fuel and electricity and in [m^2] for thermal insulation.

transport fuel production and use emits 94 kg CO_2 eq. per GJ, whereas straw ethanol emits only 14 kg CO_2 eq. per GJ, yielding a potential savings of 80 kg CO_2 eq. per GJ. When substituting straw for FFCs in electricity generation, FFC emits 183 kg CO_2 eq. per GJ, while straw emits 179 kg CO_2 eq. per GJ, and straw pellets emit 175 kg CO_2 eq. per GJ. Straw pellets have higher life cycle emissions due to pelletization (see SI III for results per LC stage).

Straw-based building insulation emits 12 kg CO_2 eq. per m^2 during production but stores −5 kg CO_2 eq. per m^2 as biogenic carbon, totaling 7 kg CO_2 eq. per m^2. Compared to traditional insulation materials (glass wool, rock wool, and expanded polystyrene), straw offers potential savings of 3, 7, and 35 kg CO_2 eq. per m^2, respectively.

For additional details regarding the impacts per LC stage for the energy and construction use cases, kindly consult SI III.

Results in figure 4 are presented as kg of CO_2 eq. per functional unit: kg CO_2 eq. per GJ for fuel and electricity, and kg CO_2 eq. per m^2 for thermal insulation. To compare avoided emissions across sectors, we converted results: 1 ton of straw equals 4 GJ of biofuel, 5.3 GJ of electricity, or insulation for 28 m^2, based on material assumptions for selected use cases. Refer to table 1 for the conversion from per functional unit to per ton of straw. The highest emission reduction potential is achieved by using straw as thermal insulation (saving 980 kg CO_2 per t of straw), followed by electricity generation (saving 949 kg CO_2 per t of straw), and straw pellet production for electricity (saving 928 kg CO_2 per t of straw).

3.2. Temporal carbon storage

The delayed emissions through temporal carbon storage were calculated with the average annual carbon accumulation rate within the respective system, i.e. the soil and the building stock. No carbon storage was considered for the energy use cases. The accumulation rate of carbon in soil was taken from Powlson *et al* (2008) with 11% during the first 20 years, decreasing to 4% (year 20–50) and plateauing at 3% after 50 years. The accumulation rate of carbon in the building stock was defined by an assumed 60 years of service life for the straw-based insulation system, based on Pittau *et al* (2018). The transfer from the biotic to the urban pool only postpones the carbon flux back into the atmosphere by the material's service life. Straw added to the building stock in the subsequent years does not further contribute to the carbon accumulated in the urban pool, as it replaces straw that has already been accounted for. Therefore, for the first 60 years, the carbon accumulation rate equals the carbon content of the material (40% or 0.4 kg of carbon per kg of biomass); after that, the carbon accumulation rate is 0%. The studied time horizon in this paper is 100 years. This results in the following 100 years-averages:

$$\theta_{\text{soil, 100a}} = 5\%$$

$$\theta_{\text{building stock,100a}} = 24\%.$$

This means that every ton of straw incorporated in the soil, leads to 50 kg of carbon retained in the soil, while for every ton of straw used for insulation, 240 kg is retained in the building stock. On average, straw incorporation can delay 184 kg CO_2/t_{straw}, while using straw as insulation material in the construction sector can delay 881 kg CO_2/t_{straw}. Note that no delayed emissions were accounted for in the energy sector use cases.

Table 1. Comparison of savings potential for straw uses. 't' refers to metric tons.

		Saving potential	Conversion factor	Saving potential
		kg CO_2 eq./GJ	GJ/1 t of straw	kg CO_2/t straw
Energy sector	Straw ethanol vs. conventional fuel	80	4	320
	Straw for electricity vs. FFC for electricity	179	5.3	949
	Straw pellets for electricity vs. FFC for electricity	175	5.3	928
		kg CO_2 eq./m^2	m^2/1 t of straw	kg CO_2/t straw
Construction sector	Straw insulation vs. glass wool	3	28	84
	Straw insulation vs. rock wool	7	28	196
	Straw insulation vs. EPS	35	28	980

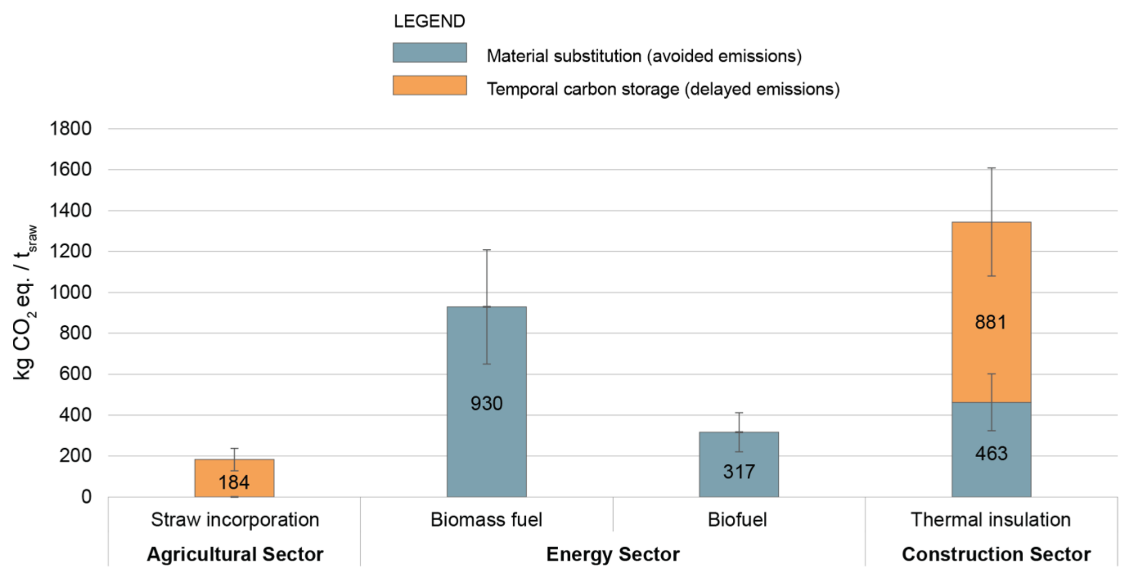

Figure 5. Climate effectiveness of different straw uses in the agricultural, energy and construction sector. *Note:* The error bars represent the uncertainties for material substitution and temporal carbon (±30%).

3.3. Total climate effectiveness

The climate effectiveness of a particular straw use is the combination of avoided emissions that can be achieved through material substitution and the delayed emissions through temporal carbon storage. Figure 5 shows the effectiveness of the use cases selected for each sector.

Considering only avoided emissions (dark blue bars in figure 5), the use of straw as a feedstock for bioelectricity has the highest climate effectiveness (930 kg CO_2 eq./t_{straw}), followed by the use of straw as insulation material (463 kg CO_2 eq./t_{straw}) and the use of straw as transport fuel (317 kg CO_2 eq./t_{straw}). No avoided emissions are achieved when straw is incorporated into the soil.

Considering only temporal carbon storage (yellow bars in figure 5), the use of straw as an insulation material has the highest climate effectiveness (881 kg CO_2 eq./t_{straw}), followed by straw incorporation in soil (184 kg CO_2 eq./t_{straw}). The use of straw in the energy sector does not allow for carbon storage.

Combining the climate benefits from material substitution and temporal carbon storage, the use of straw as an insulation material has the highest climate effectiveness with 1344 kg CO_2 eq./t_{straw}, followed by using straw as biomass fuel (electricity) and biofuel (transport). Straw incorporation has the lowest climate effectiveness.

4. Discussion

This paper analyzed and compared the climate benefits of various straw applications, introducing a new perspective on industrial symbiosis by incorporating the construction sector.

Our findings revealed that using straw as building insulation maximizes material substitution benefits and temporal carbon storage. However, it is important to note that emission savings vary based on the scenario. The more carbon-intensive the conventional system, the greater the potential to reduce emissions by using straw. For context, Buchspies *et al* (2020) found a saving of 107–610 kg CO_2 eq. per ton of straw when switching from soil incorporation to bioethanol production. In our study, we found 133–746 kg CO_2 eq. per ton of straw saved in the energy sector, excluding delayed soil emissions.

Subsequent sections provide broader context for the obtained results.

4.1. Enhancing climate effectiveness metrics

The 'climate effectiveness' indicator assesses the use of agricultural biomass residue to replace non-renewable resources and mitigating GHG emissions by quantifying avoided and delayed biogenic carbon emissions. However, the accuracy and significance of the results could be improved by refining the following:

- Using national or regional specific data for the life cycle emissions and the temporal carbon storage of a particular use.
- Improving the accuracy of transformation factors.

4.2. Considering broader sustainability factors

Widening the analysis to include environmental factors other than GHG, as well as economic and social factors can give a broader perspective on the sustainability. Soil quality dictates its capacity to support diverse ecosystem services, with carbon storage being just one facet. We must also consider other essential roles it plays, including biomass production, environmental protection, gene preservation, support for human activities, raw material source, and its geogenic and cultural heritage significance (Drobnik *et al* 2018). Analyzing potential trade-offs is crucial.

4.3. Biochar and carbon storage considerations

We did not include biochar as a carbon storage option in our study due to its known slow carbon release in soil. This posed allocation challenges since biochar is typically produced by industry before agricultural use and recent developments involve its incorporation into carbon-neutral concrete. Hence, assessing biochar's efficiency for carbon storage was beyond our study's scope. Biochar originates from the energy sector we examined and can be applied in the other two sectors.

Despite the uncertainty of results, the magnitude of difference between climate effectiveness in the agricultural and in the construction sector, gives a clear indication of the high potential and importance of considering the construction sector in the resource allocation discourse and resource governance. Policies should consider sectors jointly, instead of a detached focus on one sector. In order to shift to a circular bioeconomy, material flows across sectors must be analyzed.

4.4. Global perspectives

In 2021, the top wheat producers were the EU (138 Mt), China (137 Mt), and India (110 Mt) (FAO 2023). This study analyzed EU's potential straw use, while the US, another major wheat producer (45 Mt), is also experiencing an increased demand for insulation material due to retrofitting of existing buildings. Yet, straw availability and (local) demand in the US is distinct from Europe, as cereal is produced in places with low population density. This results in often large transportation distances from field to building site. Even though the load-bearing straw bale construction technique has its origins in Nebraska, the large-scale implementation of straw construction is challenging.

China and India, being the world's top wheat producers, show theoretical potential for scaled-up straw construction. However, in tropical climates constructive systems tend to be lightweight and well-ventilated, which is different from massive straw bale construction. In these regions, a more interesting fast-growing bio-based material is bamboo as a structural building material (Zea Escamilla *et al* 2019). The resource use of woody biomass and residues, including bamboo, should be analyzed in further studies from a forest point of view.

5. Conclusions and policy recommendations

The following insights from this study are relevant for formulating policies for using straw as a resource in the bioeconomy to contribute to reaching carbon neutrality:

- More detailed statistics on the local supply and demand of straw are necessary since long transport distances for unprocessed straw are not viable, both from an economic and environmental perspective. Reliable data on straw availability is essential for stakeholders of the agricultural, energy and construction sector for planning reliability for long-term transformation processes (within individual companies or the whole sector).
- We know from economic theory that efficient resource allocation can only occur in undistorted markets. This prerequisite is not given today for straw because (i) subsidies (e.g. for straw incorporation) and mandates (e.g. for biofuels) support particular straw uses and (ii) lacking carbon taxation hinders an economization of climate straw uses. It is recommended that current policies

regarding the use of straw are re-evaluated considering their climate effectiveness. Furthermore, it is recommended that future frameworks take a resource perspective, shifting the focus from minimizing adverse impact towards maximizing positive impacts.

- The use cases analyzed in this study are not mutually exclusive but allow a cascading use of the resource: straw begins as insulation, transforms into biofuel or power, with CCS for permanent carbon storage. Biogas can return nutrients to the field, closing the loop but only through structures that encourage cross-sector collaboration for economic advantage.
- Some of the straw uses investigated in this study are not yet well known and established in the market. In October 2021, the first European full-scale commercial plant to produce straw ethanol opened in Podari, Romania. The first large scale application of straw-based thermal retrofitting is still to be seen. It is recommended that the EU and national governments promote the further development of straw applications, thereby making biogenic materials competitive with conventional materials in terms of price and ease of use.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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