Environmental impacts of cereal straw pellets in biogas systems: A comparative life cycle assessment

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Abstract Anaerobic digestion (AD) of straw pellets is a promising technology for the production of renewable energy by tapping into previously unused material, as straw pelleting offers advantages in terms of transportation, handling and methane production potential of the material. A life cycle assessment (LCA) was carried out in accordance with ISO 14040/14044 across the entire process chain, from grain cultivation to digestate utilization, with different scenarios for the provision of straw and straw pellets as well as biogas substrate mixtures. The results of the LCA showed that a reduction in emissions can be achieved in some environmental impact categories such as global warming potential (GWP) or particulate matter formation (PM). However, the environmental impact of using straw pellets as a biogas substrate depends on the underlying boundary conditions, such as the choice of allocation method for grain cultivation, transportation distances, pelleting technology or the substrate mixture for AD used. Overall, the LCA reveals that a suitable substrate mixture incorporating straw pellets with other agricultural residues can reduce the environmental impact of biogas production and thus contribute to a sustainable supply of renewable energy.

Keywords: biogas, anaerobic digestion, straw pellets, substrate pre-treatment, environmental impacts

1. Introduction

The global trend in energy production involves a circular economy and a sustainable supply of energy sources. Some advanced methods support the economic development of energy production by utilizing waste biomass while limiting the environmental impact (Phan-Huy et al., 2023; Sun et al., 2021). The use of agricultural residues like straw in biogas plants is becoming increasingly important as they represent an efficient and sustainable alternative to conventional agricultural substrates (Gievers et al., 2024). However, the environmental impact of straw management can vary depending on the farmer's preferred use, even though energy use generally has environmental benefits (Palmieri et al., 2017). Therefore, the novel approach of straw pelleting to improve overall AD performance is evaluated in this study using an LCA approach.

2. Materials and Methods

The LCA of the use of straw pellets for biogas production was carried out on the basis of scenarios with different substrate mixtures and different pellet supply paths. For the various scenarios, which were based on exemplary substrate mixtures of agricultural biogas plants in Germany, the material and energy flows were modeled and the corresponding inventories prepared. The analysis covered all phases of the life cycle, from the production of raw and residual materials to the production of straw bales and/or straw pellets and the associated transportation activities through to biogas production and the utilization of fermentation residues. Since straw pellets can be supplied as a biogas substrate in a wide variety of ways, different supply process chains with mobile, partially mobile on-farm and stationary machinery were investigated as well (Figure 1). The analysis was carried out in accordance with ISO 14040 and 14044, using different environmental impact categories such as GWP, PM, fossil depletion, eutrophication, acidification and toxicitiy potentials (human and ecosystem).

3. Results

A significant difference in the production of pellets from straw can be attributed to the selected plant technology. Mobile pelleting from the swath and partially mobile pelleting from straw bales at the farm using tractor-drawn or truck-trailer systems is usually carried out with diesel engines and relatively low throughputs. Stationary pelleting systems generally have higher throughputs and are driven by electric motors for the pelleting itself and associated processes. The determination of the GWP missions for the three process chains using different pelleting processes is shown in Figure 2. The error indicators reflect the range of emissions from the sensitivity analysis (transport distances, energy requirements and energy supply form of pelleting).

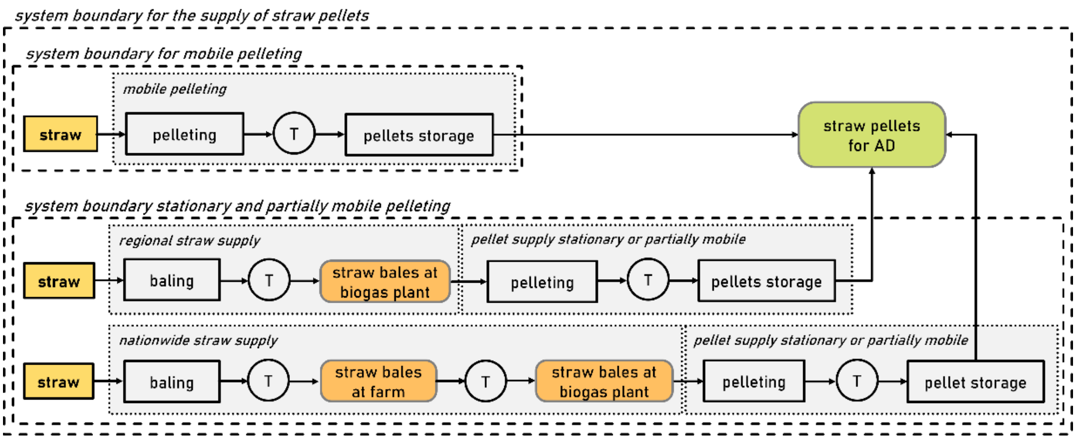

Figure 1. System boundaries of the various process chains for the supply of straw pellets for AD.

The GWP for mobile pelleting are the lowest due to the associated comparatively low diesel consumption, whereas mobile pelleting at the farm has the highest emission potential due to the necessary straw bale production and general lower throughputs compared to the field operation. In addition, it can be seen that the process chain for providing the straw bales has a smaller influence on the overall emissions compared to the very energy-intensive pelleting process.

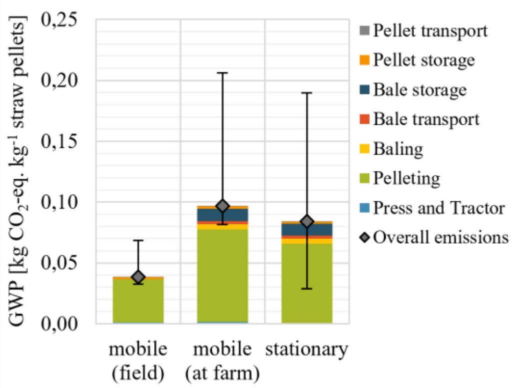

Figure 2. Influence of the pellet supply on the GWP

Besides the environmental impact of straw pellet provision, the entire process chain, considering various usage scenarios and substrate mixes, reveals a differentiated picture of the use of straw pellets for biogas production. The evaluation of scenarios with different substrate mixes shows a significant impact of livestock manure within the substrates. It can provide substantial leverage for reducing GWP emissions and fossil resource consumption. Moreover, in other impact categories such as eutrophication, human toxicity or ecotoxicity, a reduction in emissions through the use of straw pellets can be observed in all scenarios as well. The results of the sensitivity analysis for straw pellet provision show that the crucial parameters in pellet provision are the choice of allocation method for grain production, the pelleting technology used, and the transport distances for straw bales and pellets. Allocating emissions from grain production by mass or price leads to an increase in total emissions from straw supply chains in all environmental impact categories, and emissions from straw pellets can be even higher than those from conventional energy crops. Furthermore, it is shown that transporting straw pellets over 200 km causes roughly the same increase in GWP emissions as transporting straw bales over 50 km. Stationary pelleting is therefore more appropriate if straw bales are supplied locally, while mobile pelleting is suitable for transporting straw pellets over longer distances.

4. Conclusion

The LCA of the process chains of straw pellet use for AD showed that, depending on the substrate mix and supply chain of the pellets, a reduction in emissions can be achieved in some impact categories compared to the initial substrate mix without straw pellets. The parameters with a major influence on the results are the selected pelleting technology, the transportation distances of the straw bales and pellets and the digestate logistics. In addition, it was found that the amount of farm manure used in the substrate mix strongly influences the total emissions in the individual impact categories. The overall ecological effects of using straw pellets for AD therefore always depend on the underlying boundary conditions, such as the choice of allocation method for grain cultivation or the substrate mix used.

Funding: This research was funded within the “StroPellGas” project by Fachagentur Nachwachsende Rohstoffe (FNR), Germany, under the grant number 22041518.

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