REDUCING DRY MATTER LOSSES AND EMISSIONS IN MAIZE SILAGE AND BIOGAS SYSTEMS USING A SILAGE ADDITIVE CONTAINING *L. DIOLIVORANS*

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ABSTRACT

Silage additives are widely used to improve maize silage quality, yet their effects on the carbon footprint (CF) of silage production and biogas systems remain rarely studied. This study evaluated a biological silage additive containing homo- and heterofermentative lactic acid bacteria and assessed its impact on silage quality, dry matter (DM) losses during anaerobic and aerobic storage, biogas and methane yield, and the CF of maize-to-electricity generation. Maize silage prepared with (TM) and without silage additive (UM) was stored for 112 days and monitored during nine weeks of aerobic exposure. TM showed improved fermentation, higher acetic acid concentrations, strong suppression of yeasts and molds, markedly enhanced aerobic stability (72 h → 223 h), and substantially lower DM losses (21.5% → 5.21%). Biogas and methane yields increased by 5.9% and 6.8%, respectively. Using Global Warming Potential over a 100 year time horizon (GWP100), TM reduced the CF by 13.3% at the ensiling stage and by 6.9% at electricity generation stage compared to UM. Overall, the additive improved preservation efficiency and methane recovery, lowering the climate impact of maize-based biogas systems primarily by reducing losses rather than altering emission processes, although biogenic CO_2 emissions were not considered. exposure and reduced yeast and mold counts ($p < 0.01$).

Keywords: carbon footprint, silage additive, biogas, maize silage

INTRODUCTION

Maize silage is a key substrate for biogas production, with biogas yield strongly depending on silage quality (FNR 2016; Vervaeren *et al.* 2010). Silage additives have been shown to improve fermentation and reduce dry matter (DM) losses and spoilage, thereby affecting biogas yield and environmental impact (Borreani *et al.* 2018; Wróbel *et al.* 2023). However, the influence of silage additives on the carbon footprint (CF) of maize-based biogas systems remains rarely studied. This study therefore investigates the effects of a biological silage additive on silage quality, biogas yield, and CF, with the aim of assessing whether improved fermentation not only stabilizes maize silage but also reduces the CF of biogas-to-electricity generation.

MATERIAL AND METHODS

Maize (36.2% DM) was harvested from a farm in northern Germany in September 2023, weighed before ensiling, and divided into two silos: an untreated control (UM) and a treated silage (TM). TM was inoculated with a mixture of homo- and heterofermentative lactic acid bacteria (LAB) (*L. diolivorans*, *L. buchneri*, *L. rhamnosus*) at 250,000 CFU/g FM. Silos were sealed 112 days (anaerobic phase) and then opened (aerobic phase); silage quality was monitored over nine weeks of aerobic exposure. Analyses included pH, lactic and acetic acids, yeast and mold counts, aerobic stability (Honig, 1990), and biogas production assessed by batch tests according to VDI 4630. Fresh matter losses during anaerobic ensiling phase and aerobic fed-out phase were calculated from the difference between harvested and fed-out material. Treatment effects between UM and TM were analyzed using one-way ANOVA ($p < 0.05$). CF assessment followed ISO 14067 using a cradle-to-grid life cycle assessment and were performed to quantify and compare the CF associated with a) ensiling (cultivation & ensiling) and b) electricity generation (entire chain - cultivation, ensiling, digestion, and electricity generation in a combined heat and power unit). Functional units were 1 kg FM for ensiling and 1 kWh_{el} for electricity generation. The CF evaluation was applied using the IPCC (AR6) Global Warming Potential over a 100 year time horizon (GWP100) characterization factors (IPCC, 2021), which include fossil CO_2 and CH_4, and N_2O emissions, while assigning biogenic CO_2 a global warming potential of zero and thus excluding it from the climate impact assessment.

RESULTS AND DISCUSSION

The silage additive significantly improved silage quality and preservation, as reflected by higher acetic acid concentrations (TM: 3.58% DM; UM: 1.40% DM) and pronounced suppression of spoilage microorganisms. Yeast counts decreased significantly from 27,200 CFU/g FM in UM to 180 CFU/g FM in TM, indicating effective inhibition of aerobic spoilage (Table 1).

Tab. 1: Average values of the monitoring parameters for silage quality of the control (UM) and with a biological silage additive treated maize silage (TM) for three months opening period

Parameter	Unit	Maize silage		
		UM	TM	p-value
DM	g/kg FM	331.77 ± 26.90	348.01 ± 22.09	0.1047
oDM	g/kg DM	980.74 ± 43.90	981.58 ± 37.00	0.5989
Lactic acid	% DM	5.79 ± 1.97	4.31 ± 1.01	0.0236
Acetic acid	% DM	1.40 ± 0.33	3.58 ± 0.48	< 0.0001
pH	–	3.66 ± 0.11	3.83 ± 0.08	< 0.0001
ASTA	h	72.40 ± 16.99	223.20 ± 16.35	< 0.0001

DM= Dry matter. FM = Fresh matter. ASTA = Aerobic stability time assessment. CFU = Colony forming unit

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Accordingly, aerobic stability increased significantly from 72 h to 223 h, substantially reducing the risk of deterioration upon air exposure. As a result, DM losses declined from 21.5% in UM to 5.21% in TM. Although heterofermentative LAB such as *L. buchneri* may cause additional DM losses through CO_2 formation during anaerobic fermentation, the present results demonstrate that under practical conditions the benefits of improved aerobic stability and reduced yeast activity clearly outweighed potential fermentation-related losses (Wróbel et al. 2023). Overall, the additive shifted fermentation toward reduced spoilage and DM losses, thereby increasing the amount of usable substrate for downstream utilization.

Biogas production

Biogas and methane yields of the silages were evaluated over the full observation period. TM achieved a higher biogas yield (241.67 ± 17.08 Nl/kg FM) than UM (228.26 ± 12.45 Nl/kg FM), corresponding to an increase of 5.9%, while methane yield increased by 6.8% from 122.12 ± 12.45 Nl/kg FM for TM to 130.38 ± 9.16 Nl/kg FM for UM.

Carbon footprint

At the ensiling stage, CF under GWP100 amounted to 37.24 g CO_2-eq kg/FM for TM and 42.93 g CO_2-eq kg/FM for UM, corresponding to a 13.3% reduction. At the electricity generation stage, TM showed a 6.9% lower CF than UM, mainly driven by loss-induced upstream replacement (i.e., cultivation and input requirements rise when DM losses increase). However, GWP100 does not reflect that biogenic CO_2 released through DM losses represents foregone methane potential and thus lost energy generation. Accounting for biogenic CO_2 would therefore further accentuate CF differences between treatments.

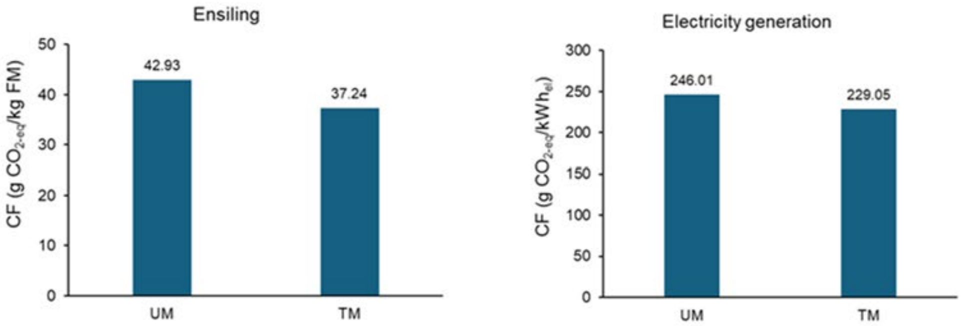

Fig. 1: Carbon footprint of untreated (UM) and treated maize silage (TM) under Global Warming Potential (GWP 100) for the ensiling process (a) and the full pathway up to electricity generation (b) from biogas

CONCLUSION

Even without accounting for biogenic CO_2 emissions, this study demonstrates that the silage additive containing *L. diolivorans* reduces the climate impact of maize silage production and maize-based biogas systems by minimizing dry matter losses and improving substrate efficiency. Improved fermentation quality and aerobic stability preserve more biomass for methane production, slightly increase methane yield, and reduce land and input requirements, thereby lowering emissions per unit of electricity produced. The results highlight silage additives as an effective method to mitigate climate impact when combined with good management.

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