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Zusammenfassung der kumulativen Dissertation

Ensiling and anaerobic digestion of plant biomass for energetic and material utilization

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Every year, about 140 gigatonnes of residual plant biomass is generated globally from agricultural practices, with resultant environmental and economic consequences.[1] These mass flows are potential substrates for biofuel production. Sugar beet leaves are examples of an agricultural residue that is available in large quantity in Germany and other countries with moderate climate. It is a by-product of sugar beet harvesting, with an estimated 18 million tons produced in Germany. Despite its availability, little attention has been paid to the use of sugar beet leaves for anaerobic digestion (for biogas production) and anaerobic fermentation (for medium chain carboxylates production). However, sugar beet leaves (like many other wet biomass) is a seasonal biomass, available only during the harvesting of sugar beet. Consequently, the biomass needs to be preserved so that it can be made available whenever it is required as a substrate for biogas production or for anaerobic fermentation. One effective and cost friendly method of preservation of wet biomass like sugar beet leaves is ensiling.

An important factor to consider during ensiling is the use of additives. Many commercially available additives like lactic acid bacteria (LAB) improve the quality of silages but have little or no effect on their biomethane potential. In this thesis, a novel additive, developed from solid-state fermentation of vegetable raw materials, was tested on sugar beet leaves silage. The biomethane potential of ensiled sugar beet leaves increased by as much as 45.35 % at a substrate to additive ratio of 50:1 ($g_{substrate}/g_{additive}$). These results are published in **Applied Sciences (Paper 1)**.

Many of the ensiling processes reported in literature were carried out on a laboratory scale. However, there are some challenges in transferring the results from the laboratory to practical application. Laboratory experiments are conducted in small containments (e.g. airtight bags, silage jars, etc.), which allows for replication and controlled conditions. However, such laboratory experiments do not take into account the influence of gravity on silages. In practice, gravity may influence the distribution of total solids (TS), volatile solids (VS) and fermentation products within the different areas. For this reason, the effect of gravity on the quality of ensiling and biomethane potential of sugar beet leaves were investigated, using vertical columns. It was found that substrates at the top of the columns had lower silage quality compared to substrates at the bottom of the columns regarding pH and lactic acid concentration. Silages at the bottom of the columns also had a 20.9 % higher biomethane potential than silages at the top of the columns. Consequently, if such silages are to be fed directly into a reactor, there will be need to vary some operating parameters like organic loading rate. This is because, due to gravity effect, silages at the top of the columns have lower TS and VS compared to silages at the bottom. Additionally, for laboratory experiments and the small quantities needed for them, it is much easier to use hand-harvested leaves than to coordinate sampling and laboratory work with a machine-harvesting schedule. However, hand-

[1] Tripathi, Nimisha; Hills, Colin D,; Singh, Raj S.; Atkinson, Cristopher J. (2019): Biomass waste utilization in low-carbon products. Harnessing a major potential resource. In npj Climate and Atmospheric Science 2(1), p. 35.

harvesting typically yields only leaves (without beet tops) and involves less mechanical treatment of the leaves. The composition of machine and hand-harvested materials may therefore differ in TS, VS, soluble carbohydrates (due to the higher TS and sugar content in the beet tops), nitrogen (N) content and buffer capacity. Microbial degradation may start faster in the machine-harvested material due to the shredding effect at harvest, thereby leading to fermentation even before ensiling. However, in this thesis, results show that the method of harvesting had no significant effect on the biomethane potential of sugar beet leaves. These results are published in **Biofuels (Paper 2)**.

Although ensiling is a cost friendly and effective method of preserving wet biomass, substrates with very low TS content are difficult to ensile. Ensiling with low TS in usual clamp silos or in bagging ensiling leads to very challenging leachate management. Without using the leachate in anaerobic or fermentation plants, large amounts of easily degradable organics will remain out of value creation. To overcome that challenge, such substrates can be co-ensiled with substrates that have a high TS content. Regarding this challenge, water hyacinth (with a low TS content) was co-ensiled with maize straw (with a high TS content). In addition, egg shell was used as additive to improve the butyric acid content of the ensiled materials. The results show that co-ensiling with MS and egg shell powder as additive significantly improved the biomethane potential of water hyacinth. Details of the investigation of the effect of co-ensiling and egg shell additive on the biomethane potential of water hyacinth have been published in **Journal of Chemical Technology and Biotechnology (Paper 3)**.

For a sustainable biomethane production from sugar beet leaves, it is necessary to understand the overall process performance of the bioreactor for an efficient control of process parameters needed for an optimal biomethane yield. One of the ways of describing the overall performance of a bioreactor is by the use of kinetic models. Parameters obtained from kinetic models that describe a given biochemical process are sometimes specific to substrate types and process parameters. In this thesis, different kinetic models were used to predict the biomethane potential of sugar beet leaves and water hyacinth. In all cases, the biomethane potential was better predicted by the dual pool kinetic model than by the first order or modified Gompertz models as published in **papers 1, 2 and 3**.

Besides anerobic digestion for biogas production, anaerobic fermentation was also carried out to produce platform chemicals like medium chain carboxylates (MCCs). The production of MCCs are influenced by factors like initial pH and microbial community. The microbial community is strongly influenced by the inoculum source. Using an inoculum from a reactor producing caproate produced a yield of 99.55 g/kgVS of MCC from sugar beet leaves compared to a yield of 33.27 g/kgVS of MCC when a digestate from a biogas reactor was used as an inoculum. Since the economic feasibility of carboxylates production by fermentation and subsequent extraction is limited because of their low concentration in fermentation broths, it was necessary to look at the feasibility of improving the economics of the process by using the residue of refining for biogas production. An overall mass balance for the extraction of medium chain caboxylate from a fermentation broth of sugar beet leaves silage was developed. Two discounted cash flow methods; the Net Present Value (NPV) and the profitability index (PI) were used as economic indices to evaluate the economic feasibility of the sole production of MCC, as well as the combined production of MCC and biogas from ensiled sugar beet leaves. The economic indices showed that only the combined production of MCC and biogas can make the process economically attractive at the operated conditions. Details of the results is being prepared for submission **(Paper 4)**.