Anaerobic digestion of urban bio-waste and utilization of digestate as a nutrients source for biogas upgrading

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The increasing world population and needs of modern humanity are resulting in huge production of urban organic waste. Subsequently, the accumulation of urban organic waste constantly causes serious environmental problems. Thus, there is an urgent need for proper waste treatment. An efficient method to treat the organic fraction of urban waste is the anaerobic digestion (AD). The energetic output gained by the formed methane and the utilization of digestate as either high quality fertilizer or upcycling nutrients for other biotechnological routes, settle AD as a comparable method to the traditional practices (i.e. landfill, incineration, composting). To date, many decision makers still prefer to dedicate the major fraction of urban solid waste on the traditional techniques. Nonetheless, European countries have to comply with the Renewable Energy Directive targeting on 100% fossil-free energy system by 2050 and thus, AD can significantly contribute to achieve Europe's sustainability. While AD of urban organic waste is not a novel concept, there are still specific drawbacks that should be addressed in order to reach high process efficiency without instabilities in full-scale applications. For example, the major fraction of urban organic waste consists of rather intact materials that should be pretreated to boost their biodegradability. In parallel, the organic losses during the pretreatment should be minimized to reassure substrates' quality. Indeed, pulping technology has the potential to address the aforementioned technicalities and improve biomass degradability.

Apart from pretreatment methods, other constraints affect markedly the bioenergy yield. For instance, high organic loading rate (OLR) can cause reactors' acidification due to the accumulation of hydrolyzed organic matter. Subsequently, the methanogenic activity can be decreased and in terms of profitability, huge negative economic consequences are faced at an industrial scale. On the contrary, the volumetric biogas production can be maximized by increasing the OLR and consequently, the sustainability can be improved. Hence, improved understanding of the relationship between OLR and microbiome structure would be extremely helpful to design efficient feeding strategies for biogas plants using urban organic waste. Moreover, the further establishment of AD sector can be achieved through the exploration of new roadmaps for the produced biogas. However, the microbially produced gas is composed of 50-70% CH_4 and thus, cleaning steps are needed to comply with the standards for grid injection (>90% CH_4). Utilization and upcycling of both gas and liquid AD streams is needed to reach the set standards.

The aim of the present study was to evaluate the biogas production in anaerobic digesters fed with pretreated urban organic waste at long-term operation. The study was focused on the maximization of volumetric biogas production, while attention was also paid on microbial communities shifts using high throughput 16s rRNA amplicon sequencing. Subsequently, the produced digestate was evaluated as a nutrient source for pilot-scale biomethanation tests to support an efficient biogas upgrading process (>90% CH_4).

For the current study, the inoculum was provided by Hashøj full-scale biogas plant and the urban organic waste was collected after the pulping process in Holsted in Denmark. Three identical continuously stirred tank reactors (CSTRs) were employed with total and working volume of 4.5 and 3.0 L, respectively. The CSTRs were initially monitored in order to optimize the start-up period (i.e. 80 days, published data) (Khoshnevisan et al., 2018). Once steady-state conditions were achieved, the experiment was continued to the next phase. Before changing the operational conditions, a consecutive period of 10 days was demanded during which all biochemical parameters varied less than 10%. The maximization of OLR was examined by increasing the total and volatile solids of urban organic waste. In addition, a pilot reactor with a total and working volume of 800 and 500 L, respectively, was used. The pilot reactor was initially filled with 50% of the final working volume and then, operated on a fed-batch basis following an exponential feeding strategy based on previous work (Khoshnevisan et al., 2018). A maximum 10% TS in the feedstock was applied. Compared to lab-scale operation, the pilot study challenged with disturbances in the daily organic loading similar to real-life operations in which the waste flow is not completely constant and also, faced disturbances, recovery phases and steady-state periods. The digested urban bio-waste were subsequently upcycled in a pilot-scale biomethanation reactor as explained earlier (Tsapekos et al., 2021). Overall, the well-controlled tests at lab-scale provided important insights of municipal bio-waste AD, while the pilot-scale demonstration actions that are closer to full-scale operation provided a more realistic outcome for real-life applications.

As expected, the mono-digestion of urban organic waste at the lowest OLR was associated with the lowest biogas volumetric production rate (Fig. 1). At the end of the first period, all CSTRs were stabilized and the average biogas volumetric productivity of the triplicates was 1.91 L/Lr.day. Subsequently, the increment of OLR from 2.6 to 3.4 gVS/Lr.day boosted the biogas productivity to 2.32 L/Lr.day. Likewise, the further increase of OLR to 4.3 and 5.3 gVS/Lr.day increased the biogas productivity to 3.30 and 4.26 L/Lr.day, respectively. Furthermore, the concentration of volatile fatty acids (VFA) was always low (<0.5 g/L) from the beginning until the end of the experiment. The low VFA levels shows that the AD process was in balance and thus, the gradual increment of OLR was successful. At long term, the pH was slightly increased through all phases. The rationale for this observation can be found to the higher buffer capacity of the feedstock over time. Indeed, the steadily decreased substrate's dilution led to a feedstock with higher ammonium content resulting in higher alkalinity. Despite the usage of less diluted substrate in the feedstock, inhibition due to increased ammonia was not detected as shown by process monitoring (<1.8 g-NH_4/L). The absence of inhibition due to free ammonia was supported by the slightly alkaline pH (<7.7) and negligible VFA accumulation (<0.3 g/L). In addition, the obtained results revealed that the stepwise increase of OLR can efficiently boost the biogas productivity and also, lead to an efficient bio-waste treatment capacity via AD. Moreover, the microbiomes of the three CSTRs did not differ markedly, and the triplicate samples followed a similar pattern.

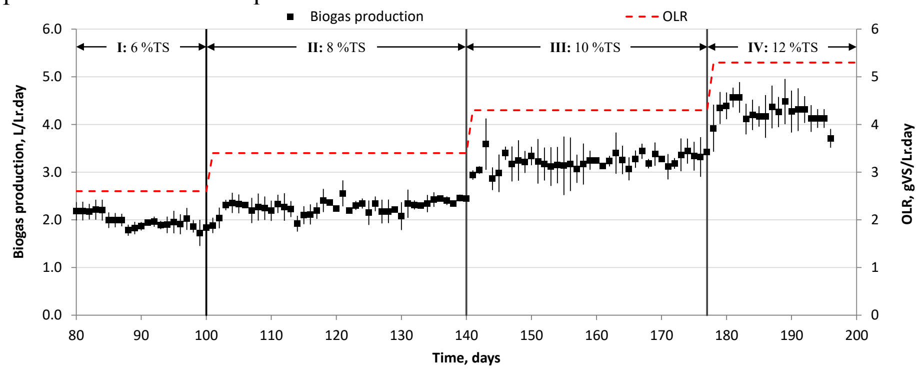

Figure 1. Biogas production using urban bio-waste at continuously stirred tank reactors.

Regarding pilot operation, at 6%TS content the biogas productivity was 1.74 L/Lr.day which was only slightly lower than the outcome of the lab tests. Despite the numerous operational challenges (i.e. alternating OLR, temperature fluctuation, on-off mixing) that were applied, a more robust community was established in the pilot reactor than the lab-tests. Microbiome reorganization during the AD of municipal bio-waste was clearly revealed. The key members during the start-up, increase of OLR and pilot operation have been identified. The results showed that the start-up strategy significantly affected the microbiome composition in the beginning of the experiments, while the community became similar as the operation continued. The augmentation of OLR introduced significant changes in microbial communities. The increase of *Synergistetes* members and the transition to versatile methanogenic metabolisms were observed in both lab and pilot reactors. However, the changes in other taxa, such as *Bacteroidetes*, *Firmicutes* and *Cloacimonetes* were diverging between lab and pilot experiment. Furthermore, the produced digestate was efficiently added to a separate pilot-scale trickle bed reactor to be used by a CO_2/H_2 fueled microbiome that was upgrading biogas. The available micronutrients (e.g. Ni, Co, Fe) in the digestate were crucial to the basal microbial functions. Following metals' concentrations over time, it was shown that nutrients were always above the lower threshold levels based on literature. Focusing on microbial ecology, microbes whose genome profile contains genes associated with biofilm formation and stimulation dominated at places inside the pilot-reactor where high nutrient abundance was available. Overall, both scales of operation provided important insights for municipal biowaste AD. High volumetric methane production was achieved in the well-controlled lab environment, while a robust microbiome able to revive after severe disturbances was formed in higher scale. Hence, the obtained results can support the further established of biowaste-based AD.

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References

Khoshnevisan, B., Tsapekos, P., Alvarado-Morales, M., Angelidaki, I., 2018. Process performance and modelling of anaerobic digestion using source-sorted organic household waste. Bioresource Technology 247, 486–495.

Tsapekos P, Treu L, Campanaro S, Centurion VB, Zhu X, Peprah M, Zhang Z, Kougias PG, Angelidaki I., 2021. Pilot-scale biomethanation in a trickle bed reactor: Process performance and microbiome functional reconstruction. Energy Conversion and Management, 244:114491.