# General Observations

Newly added text is highlighted in green in the revised manuscript. Line numbers given in the rebuttal letter at hand pertain to the revised manuscript.

# Editor comments

1. Please don't disclose author identifier in the Response to Reviewers.

After appropriate verification, we confirm that we did not disclose author information during the review.

1. High quality and meaningful graphical abstract should be provided. You can find some examples from cover image of each BITE issue. For each issue, we select a good one in these papers as cover image.

Thank you for the remark. We slightly modified the graphical abstract. After careful revision, we confirm that the graphical abstract is meaningful and correctly introduces the manuscript. If further modifications are necessary, please let us know.

1. Please do follow the guide for authors while revising your MS as given in the following link: https://www.sciencedirect.com/journal/bioresource-technology/publish/guide-for-authors

Thank you for your remark. We carefully considered the guide for authors while revising the manuscript.

1. Avoid articles in the title (THE, A and AN).

After careful verification, this remark seems to be not applicable: no articles (the, a, an) used in the title.

1. No acronyms allowed in the title.

After careful verification, this remark seems to be not applicable: no acronyms were used in the title.

1. Avoid keywords that are in the title.

After careful verification, this remark seems to be not applicable: none of the keywords appear in the title.

1. Each highlight should not exceed 85 characters with space.

After careful verification, this remark seems to be not applicable: highlight 1 has 83 characters including spaces; highlight 2 has 71 characters; highlight 3 has 84 characters; highlight 4 has 84 characters; highlight 5 has 82 characters.

1. Introduction must NOT be more than 3 pages long.

Thank you for your comment. We reduced the introduction section, such that it is now exactly 3 pages long. Modifications were applied in lines 30, 33, 35, 38, 40, 47, 48, 52, 54-59, 62-64, 66, 67, 71, 72, 74, 81, 82, 88, 90, 92, 98, 100-102, 104, 106, 109.

1. Page number and line number should be provided. Line number should be continuous from page 1.

After careful verification, this remark seems to be not applicable: page and line number are already present.

1. Please avoid right justification of the text.

After careful verification, this remark seems to be not applicable: text is not right justified.

1. Maximum number of the pages allowed is 35 for research article (50 for review articles) with font size no less than 12 for all sections including references and double spacing for all sections. Tables/Figures should be placed in each page. ONLY 6 Figures/6 Tables are allowed.

After careful verification, this remark seems to be not applicable: the manuscript (from title to figures/tables) consists of exactly 35 pages, 6 figures and 2 tables.

1. E-supplementary figures and tables must not be quoted in text as Fig S1..Table S1.., etc. These should be mentioned as (see supplementary material) in the text at relevant places and after the "Conclusion" in a sentence as "E-supplementary data for this work can be found in e-version of this paper online".

Thank you for the comment. We verified that no direct references of figures or tables in the supplementary material were present in the text. However, as suggested, the phrase “supplementary information” (SI) was replaced by “supplementary material” (SM) throughout the manuscript text as well as in the SM itself.

1. Indicate the location of (see supplementary materials) in text in yellow highlight.

Thank you for the comment. Text was highlighted in yellow when necessary.

1. In research articles, do not include any table comparing literature with your findings ether in the main MS or SI. You can discuss the main findings in the text itself.

After careful verification, this remark seems to be not applicable: no table comparing literature with our findings was or is present.

1. Supplementary Material can only consist of maximum five tables/figures together and must NOT contain any text and/or refs.

Thank you for your comment. We moved the derivation section of the gas storage model equations into the methods section of the main manuscript. Now the Supplementary Material (SM) consists of two figures, three tables. Additionally, as specifically requested by reviewer #2, the full set of model equations was added to the SM to ensure reproducibility of the simulation results. This is a very common practice for modelling and simulation papers.

Please let us know if further modifications of the supplementary material are required.

1. There is no need for two decimal places especially for efficiency. It is a gross term. It is fine without decimal place. Pl. check and be consistent throughout the MS.

After careful verification, this remark seems to be not applicable: the efficiency was stated as 36% in Table 1.

1. Abstract should NOT be more than 250 words and Conclusion should NOT be more than 150 words.

After careful verification, this remark seems to be not applicable: The abstract consists of 168 words and conclusions of 94 words.

1. Do not use first person (we, our, us) in text.

After careful verification, this remark seems to be not applicable: First-person plural was never used in the manuscript text or in the supplementary material.

1. Do not include any non-English references.

Thank you for your comment. We replaced the German reference „Fachagentur für nachwachsende Rohstoffe e.V. (2021)“ with AgSTAR (2020): *Anaerobic Digester/Biogas System Operator Guidebook*. A Guidebook for Operating Anaerobic Digestion/Biogas Systems on Farms in the United States, cf. line 590, as well as Wu, D.; Peng, X.; Li, L.; Yang, P.; Peng, Y.; Liu, H.; Wang, X. (2021): *Commercial biogas plants: Review on operational parameters and guide for performance optimization*. Fuel303, 121282, cf. lines 501, 502.

1. Do not include Pre-prints in the reference list.

Thank you for your comment. This is no longer applicable, since during the review, the paper Delory et al. (2025) has been published. The list of references was updated accordingly, cf. lines 631-633.

1. Please number the references in alphabetical order, and no more than 50 references are allowed for research article, 150 for review article and 35 for short communication. Font size 12 and double spacing.

Thank you for your comment. References are ordered alphabetically. Font size is set to 12 and double spacing is activated. The number of references was appropriately reduced to 53. Three additional references were explicitly requested by reviewer #2, therefore we kindly ask for an exemption in this matter. Please let us know if further changes are required.

1. The journal does not publish conventional spectra (X-ray, FTIR, UV, NMR, etc), SEM photographs, single data column tables, or biochemical pathways (unless essential), or simple one line figures.

After careful verification, this remark seems to be not applicable: no simple single data column tables, no one line figures or any of the other data are present in the manuscript.

1. Do not embed Tables/Figures in the main text. They should be provided separately each in one page..

After careful verification, this remark seems to be not applicable: all tables and figures are not embedded in the main text, but are displayed on separate pages within the manuscript.

1. No acronyms when they appear first.

After careful verification, this remark seems to be not applicable: acronyms are always defined after their first definition. Acronyms in the abstract are re-introduced in the main text.

1. All data must be statistically analyzed and compared. Provide error bar for all figures. In Tables, provide standard deviation. Pl. provide details in the footnote about how many samples/analyses were carried out and use of any acronyms.

After careful verification, this remark seems to be not applicable: Figure 3 contains box plots, and Figures 4-6 show simulation results of closed-loop system performance, for which error bars do not apply (uncertain scenarios are not shown). In Table 1, variation coefficients (VS) are provided in the bottom row, with corresponding numbers of samples in the last column. In Table B.3 in the supplementary material, standard deviations for uncertain influent concentrations are given with the same number of decimal places as mean values.

1. In all Tables the significant figs for decimal all the values should not be different for mean and SD.

After careful verification, this remark seems to be not applicable (cf. editor comment 25): In Table B.3 in the supplementary material, standard deviations for uncertain influent concentrations are given with the same number of decimal places as mean values.

1. Avoid acronyms in heading/subheading.

Thank you for the comment. Now section “Dynamic AD model: ADM1-R3” is called “Dynamic anaerobic digestion model”; section “AD plant dimensioning” is now called “Anaerobic digestion plant dimensioning”; section “Simplified scenario tree design for anaerobic AD model” is now called “Simplified scenario tree design for anaerobic digestion model”; “Multi-stage MPC performance” is now called “Robust controller performance”; and “Comparison of robust and nominal MPC” is now called “Comparison of robust and nominal controller”.

1. Pl. keep self-citation to no more than 3.

Thank you for the comment. We appropriately removed corresponding references.

1. Provide more indepth mechanistic discussion.

Thank you for your comment. We elaborated on the model in more detail, as also requested by reviewer #1, cf. lines 54, 55-59, 62-64, 66, 67. Additionally, we moved the gas storage model definition from the supplementary material into the methods section cf. lines 145-159.

1. Please do NOT use acronyms in abstract when they appear first.

After careful verification, this remark seems to be not applicable: We introduced the abbreviations AD (anaerobic digestion) and NMPC (nonlinear model predictive control) in the abstract when they were first used.

1. Provide one concluding sentence in abstract about the "TAKE HOME MESSAGE".

Thank you for your comment. We modified the last sentence of the abstract and believe that it now adequately summarizes the take home message of the manuscript, cf. lines 22-25.

1. Please, remove the acronymes from the Conclusions section, Table headings and Figure captions. Conclusions, Tables and figures must be self-explanatory.

Thank you for the remark. We replaced abbreviations where necessary.

1. E-supplement figures and tables can not be quoted in text directly (as Fig S1..Table S1..etc). These can only be mentioned in a sentence following the conclusion.

After careful verification, this remark seems to be not applicable: No direct references of figures or tables in the supplementary material are present in the manuscript.

1. While submitting the revised manuscript, please double check the author names provided in the submission. PLEASE be noted that NO authorship change was allowed after the first submission.

Thank you for the information. We did not add any new co-authors or changed the order of the authors.

# Reviewer #1

1. This study developed a robust multi-stage MPC framework to optimize substrate feedings with uncertain influent macronutrients to an agricultural AD plant, and the results were good. It should be interesting to the readership of Bioresource technology, I think the manuscript can be considered for publication after major revision.

Thank you for positively evaluating our research. We are glad that our efforts to progress in the field of biogas technology are recognized.

1. To highlight the innovation of this paper, the authors should clarify the differences and advancements between the model in this paper and previous models in the Introduction section.

Thank you for your remark. Accordingly, in the introduction section, we further highlighted the differences of the model used in this study and previously proposed models, including data-driven models, cf. lines 54-59, 62-64, 66-67.

1. Lines 163-166: Crop straws are typical agricultural AD substrates and should be considered in this paper.

Thank you for your comment. We recognize that crop straws are abundant and valuable agricultural residues. However, our study focuses on agricultural anaerobic digestion (AD) plants in Germany, which has been further clarified in lines 47-48, 175-177. In this country, crop straw plays a sub­or­di­nate role as an AD substrate. Instead, the largest shares of AD substrates (fresh matter based) are comprised by cattle manure, maize silage, grass silage and sugar beet silage (Daniel-Gromke et al., 2018; Hahn et al., 2014; Wu et al., 2021).

However, our methodology can in principle be applied to crop straws and food waste as well. Given an appropriate substrate characterization and corresponding uncertainty bounds, we expect slightly different resulting feeding patterns compared with the ones presented in the manuscript.

To best incorporate your remark in the manuscript and underscore its relevance, we modified the text of the manuscript at various locations, cf. lines 47-48, 175-177, 591, 594-595.

If you believe that further modifications are necessary, please provide specific information as to which aspects of the simulations need to be adjusted, e.g. with which concrete fresh matter quantities you wish to consider crop straws, and in which simulation scenario, e.g. as disturbance feeding.

1. Food waste is also a commonly used raw material in AD plants. Is it applicable to the model established in this paper?

Thank you for your thoughtful inquiry. Yes, in principle, the ADM1-R3 is capable to describe anaerobic digestion of multiple anaerobically degradable substrates, including food waste. This requires a suitable substrate characterization. Additionally, the methodology of multi-stage model predictive control can in principle be applied to uncertain influent concentrations of food waste. However, due to the usually high lipid content of food waste, the method to compute the nominal influent concentrations described in this study is not ideally suitable for food waste. Furthermore, the scope of this study lies primarily on agricultural substrates used in anaerobic digestion plants in Germany, for which food waste is not among the most prevalent substrates, cf. rebuttal to comment 2.

We clarified this question in the manuscript in various locations, cf. lines 197-198, 594-595.

1. Some words in Figure 1 (e) are not clear. Please revise them for easier reading.

Thank you for your remark. The bottom subfigure 1 (e) is indeed not well visible. Therefore, we increased the figure resolution and font size of the respective figure text. For a high-resolution image, please also consider the separately uploaded PDF version of the image.

1. Line 177: "where crude CH include lignin" - what does CH refer to?

CH abbreviates “carbohydrates”. We carefully verified that this abbreviation is introduced in line 124. For better readability, we slightly reformulated the sentence, cf. lines 185-186.

# Reviewer #2

1. In this paper, the authors address the robust control design of an anaerobic digester (AD) aimed at maximizing biogas production in response to demand from a combined heat and power unit (CHP) and gas storage volumes (GS). The robust control approach is based on a multi-stage nonlinear model predictive control (MS-NMPC), which is applied to a simplified ADM1 model suitable for precise prediction of gas production rates enhanced by slow- and fast-degradable fractions of carbohydrates.

In recent years, several MPC and NMPC designs have been applied to anaerobic digesters (AD), aimed at both single and co-substrate degradation and biogas production. In this paper, the authors applied MS-NMPC aimed at biogas production using multi-substrate feeds, considering uncertain influent macronutrients.

I have several comments that I believe are necessary to address to strengthen the paper's scope and contribution. These comments are as follows:

Thank you for positively evaluating our research. We are glad that our efforts to progress in the field of biogas technology are recognized, and are convinced that having modified the manuscript according to your comments has improved its quality.

1. Introduction: I believe that some relevant contributions related to the focus of the paper have been overlooked, for instance:
   1. Mendiola-Rodriguez, T. A., & Ricardez-Sandoval, L. A. (2022). Robust control for anaerobic digestion systems of Tequila vinasses under uncertainty: A Deep Deterministic Policy Gradient Algorithm. Digital Chemical Engineering, 3, 100023.
   2. Tawai, A., & Sriariyanun, M. (2022). Nonlinear Optimization‐Based Robust Control Approach for a Two‐Stage Anaerobic Digestion Process. Journal of Chemistry, 2022(1), 8966350.
   3. Yoshida, K., & Shimizu, N. (2020). Biogas production management systems with model predictive control of anaerobic digestion processes. Bioprocess and biosystems engineering, 43(12), 2189-2200.

Thank you for your constructive suggestions regarding missing relevant research articles. We added the paper of Mendiola-Rodriguez et al. (2022) in the introduction for their valuable contribution to data-driven modelling and robust MPC of anaerobic digestion with parametric uncertainty, cf. lines 57-59 and 88.

1. MS-NMPC design using a medium-size phenomenological model: In my opinion, the paper requires a depth thorough discussion and justification of the practical implementation of the proposed MS-NMPC in two aspects:
   1. (i) Despite the ADM1-R3 model providing a robust prediction of biogas production, I believe that a sensitivity analysis of the model parameters is required to include some parameters in the uncertain scenarios for the robust NMPC design, and not only the uncertain substrate characterization.

Thank you for your valuable remark. We acknowledge that many model parameters cannot be identified uniquely, and are thus uncertain. We further recognize that the influence of parametric uncertainties can have a major effect on simulation results. Indeed, this should be properly investigated, e.g. by means of a sensitivity analysis. However, due to the strict limitations of max. 35 pages of the manuscript, an in-depth investigation of a sensitivity analysis would exceed the scope of the present paper.

However, we underlined the relevance of a thorough investigation of parametric uncertainty by means of a sensitivity analysis in the methods, results and discussion, and conclusion sections, cf. lines 173-175, 593, 603-604.

Indeed, the question of parameter uncertainty and sensitivity analysis is subject to current investigations which we expect to publish in the near future.

* 1. (ii) In the numerical simulations and evaluation of the MS-NMPC, I believe that both additional uncertain model parameters and the introduction of a state estimator for the used model will lead to significant computational cost and optimization convergence problems. These are essential aspects that should be addressed to provide a complete evaluation of the robust NMPC approach.

Thank you for your valuable comment. It is correct that adding further uncertain parameters and including a state observer will increase the computational complexity. Therefore, we further stressed these aspects in the results and discussion section, cf. lines 582-584 for the aspect of additional uncertain parameters, and lines 466-467, 587, 603-604 for a state observer.

1. Supplementary material: To be reproducible, the numerical simulation results, it is suggested that the authors provide in supplementary material model equations, parameters, and initial conditions.

We appreciate your comment. For simulation results to be reproducible by the readers, we added a full set of model equations, parameters, initial conditions and influent concentrations in the supplementary material.