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Plant-wide Modelling of a Biorefinery: Microalgae for the Valorization of Digestate in Biomethane plants

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ABSTRACT

Microalgae cultivation on liquid digestate from the anaerobic co-digestion of agricultural feedstocks is an interesting option for digestate nutrient removal and resource recovery coupled to value-added biomass production. In this paper, a first-principle plant-wide modelling of the process is described. Two well-established models for anaerobic digestion (IWA – ADM1) and algae-based bioremediation processes (ALBA) were considered and modified with necessary equations and extensions to develop a coherent interface between the state variables of the two models. The resulting system is composed by highly non-linear and non-smooth DAEs. Open-loop scenario analysis for different upstream co-digester design and operating conditions was carried out to assess the impacts on the downstream microalgae outputs. It highlighted the importance of a proper biorefinery design and yet a noteworthy robustness of the system performance. The exploitation of the model can facilitate: a more realistic assessment of the process's technical-economic feasibility and the design/validation of classical and advanced feedback control strategies.

Keywords: Plant-wide modelling, Anaerobic co-digestion, Microalgae bioremediation, Digestate valorisation.

I. INTRODUCTION

The production of bio-methane in Europe, currently supported by regulatory and economic tools, is increasing. Growing phototrophic microalgal biomass on the liquid fraction of bio-methane plant's digestate is an interesting possibility for the low-energy request, high potential for nutrients recycling, and simultaneous valorisation of CO_2 from biogas upgrading. Some microalgae strains have interesting plant's bio-stimulating properties, making them particularly suitable for the integration of algal nutrient recovery in a highly growing market. To assess the techno-economic feasibility of this biorefinery approach, a plant-wide model was developed integrating previously validated mathematical models and developing the required interfaces [1]. The plant-wide modelling framework includes two main mechanistic grey-box (uncertain parameters) physico-chemical and biological three-phase (liquid, solid, gas) models. The bio-methane plant model (agri-AcoDM) is based on the IWA ADM1 model [2], that was validated over a wide range of operational and feeding conditions [3]. The latter has been extended to account for phosphorous (P) transformations and for the non-ideality of the equations in the pH sub-model [4]. For the case studies of interest, it was proved that was reasonable to neglect ion-pairing equations, considering only major calcium and magnesium salt precipitates. For the modeling of the hydrolysis of multiple and complex feedstocks, some original state variables have been de-lumped [5]. The ALBA model [6] was used to predict the growth of algae-bacteria consortia in outdoor raceway ponds (RWP): the original model, validated on synthetic wastewater and liquid fraction of digestate, was integrated to consider organic acids in the influent. The precipitation of major P salts was also integrated, in continuity with the agri-AcoDM `block`. The evolution of temperature in the RWP system (either open or covered with single- or double-covered greenhouses) is a key factor for optimal algal growth and was modelled with a validated greenhouse pond system's (GPS) mechanistic model [7], integrating also temperature's feedback control to maintain the culture within strain-specific optimal ranges. Two solid-liquid (S/L) separation units were considered (a screw press followed by cationic polyelectrolyte-assisted flocculation and centrifugation) to reduce digestate turbidity and guarantee light penetration in the algae pond. A "Copp-like interface" was implemented to properly relate the agri-AcoDM to the ALBA state variables, by lumping and redistributing the chemical oxygen demand (COD), carbon (C), nitrogen (N) and P contents; mass conservation was guaranteed by inorganic dissolved nutrients as sources or sinks [4].

The paper is organized as follows: Section II illustrates the model structure; Section III recalls the case study; in Section IV the simulation results are discussed; finally, in Section V a conclusion is drawn.

II. MODEL STRUCTURE AND IMPLEMENTATION

The model was implemented using Modelica, an open-source, high-level, declarative and object-oriented modelling language employing the free OpenModelica interpreter (Fig. 1) [8]. The overall differential algebraic equation (DAE) system is defined as Eq.1, where $\boldsymbol{x}$ and $\boldsymbol{z}$ are dynamic and algebraic variables respectively, $\boldsymbol{u}$, $\boldsymbol{\theta}$ and $\boldsymbol{y}$ are inputs, fixed parameters and measurable outputs respectively. Functions $\boldsymbol{f}$ and $\boldsymbol{g}$ are highly non-linear (in some cases $\in C^0$).

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{z}, \boldsymbol{u}, \boldsymbol{\theta}) \\ \boldsymbol{0} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{z}, \boldsymbol{u}, \boldsymbol{\theta}) \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{z}, \boldsymbol{u}, \boldsymbol{\theta}) \end{cases} \tag{1}$$

Parameters $\boldsymbol{\theta}$ are partitioned to the concentration (kg m^{-3}) of variables in the i^{th} co-feedstock input flux ($\boldsymbol{\theta_{u,i}}$) and stoichiometric, physico-chemical and kinetic parameters ($\boldsymbol{\theta_p}$). Within a new Modelica library, each unit `block` of the **`biorefinery`** class has been defined by a dedicated model equipped with the necessary input/output information ports and physical connectors. In particular, two different types of connectors have been created to allow for the exchange of gas media (biogas, as perfect gas mixture) and of non-ideal heterogenous solid/liquid mixtures (feedstocks, digestate, algae suspension): the latter is agri-AcoDM- and ALBA-specific, due to the different state variables of the two models. For this reason, a dedicated model (the "Copp-like interface") to convert the two model's state variables have also been considered in the library. Of particular interest, is the exploitation of the **`stream`** connectors in the declaration of the interface components, to allow for immediate and flexible mixing of the different co-feedstocks. In the following, the sub-models in Fig. 1 are briefly described.

(a) Model inputs

The inputs to the **`biorefinery`** model are process design fixed parameters, weather data for the GPS and influent feedstock's nutrient compositions for agri-AcoDM. The latter can be set both as $\boldsymbol{\theta_{u,i}}$ or from `CombiTimeTables` to consider feedstock variability. Dedicated conversions' equations between composition's data and model's state variables are performed for both pumpable and stock-piled feedstocks [3, 9].

(b) Anaerobic co-digester (agri-AcoDM)

From the hydraulic standpoint, the reactor is a closed and completely stirred tank reactor (CSTR) with constant volume. The ordinary differential equation (ODE) system state variables are 38 concentrations (kg m^{-3}) in the specific media of either bacterial populations or organic/inorganic chemical total components, dissolved and gaseous. The state variables interact with each other via biological (hydrolysis, uptake, decay) and physico-chemical (precipitation/dissolution and gas-liquid mass transfer (two-film theory)) process rates r (kg m^{-3} s^{-1}). The generic ODE equation for the liquid-solid mixture mass balances is:

$$\begin{cases} \dot{\boldsymbol{x}} = \frac{\sum_{i=1}^{n} u_i}{V}(\boldsymbol{x_{in}} - \boldsymbol{x}) + \mathbf{K_G}\mathbf{r}(\boldsymbol{x}, \boldsymbol{\theta_p}, \boldsymbol{z}) \\ \boldsymbol{x_{in}} = \frac{\sum_{i=1}^{n} u_i \boldsymbol{\theta_{u,i}}}{\sum_{i=1}^{n} u_i} \end{cases} \tag{2}$$

where $\boldsymbol{x}$ are the state variables, V (m^3) is the reactor volume, u_i (m^3 d^{-1}) is the volume flowrate of the i^{th} input co-feedstock and $\mathbf{K_G}$ is the transposed stoichiometric Gujer matrix, that guarantees COD and atomic mass conservation, extended and modified according to the new variables and processes introduced. Note that $\boldsymbol{r}$ depends on $\boldsymbol{z}$ too, as the latter refers to physico-chemical quantities characterized by very fast dynamics and later described. For gaseous states, Eq.2 still holds and has a null influent contribution, V is the reactor headspace volume and u_i is the biogas outflow, regulated by a SISO PI controller that keeps the reactor headspace slightly over atmospheric pressure. An example of the model non-linearities is shown in Eq.3, defining the general structure of a bioprocess kinetic rate r representing the gross growth of a bacteria population with concentration X_{ac} (acetoclastic methanogens), i.e.:

$$r = \mu_{max} f_{pH} \frac{K_{i,nh3}}{K_{i,nh3} + S_{nh3}} \min_j \left(\frac{S_j}{S_j + K_{s,j}} \right) X_{ac} \tag{3}$$

where μ_{max} (d^{-1}) is the maximum specific growth rate and f_{pH} is an empirical sigmoidal function that describes pH inhibition. Free ammonia (S_{nh3} (M)) inhibition is represented by the non-competitive function which shape is defined by $K_{i,nh3}$ (M). Growth limitation by nutrient uptake is described by secondary Monod functions subject to the Liebig's minimum law, where $K_{s,j}$ (M) is the half-saturation constant for the nutrient S_j (j = {inorganic C, N, P and acetic acid}) [2]. A multiplicative term that depends on the sign of the saturation index SI is used to discriminate precipitation ($r_{p,+}$) from dissolution ($r_{p,-}$) kinetics for

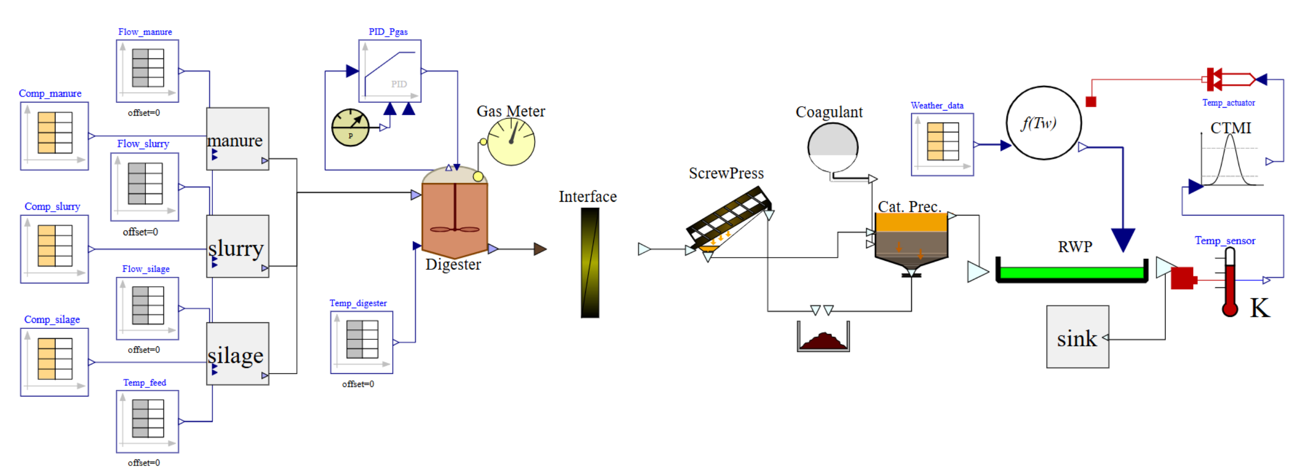

Figure 1: Plant-wide **`biorefinery`** class in the OMEdit diagram view. The GPS model is referred to as *"f(T_w)"*. "Cat. Prec." (cationic precipitation) refers to be flocculation unit. The Copp-like interface was called "Interface".

each salt with concentration X_{salt}, as in Eq.4:

$$r_{p,\pm} = \frac{1 \pm sign(SI)}{2} k_{cryst} X_{salt} \left[\left(\frac{\prod_{i=1}^{n_r} a_{i,j}}{K_{sp}} \right)^{\frac{1}{n_r}} - 1 \right]^2 \quad (4)$$

where $a_{i,j}$ (M) are the activities of the chemical ionic species involved in the process, j is their stoichiometric coefficient, n_r is the number of moles of reactants, K_{sp} (M) the solubility product constant and k_{cryst} the kinetic constant (s^{-1}) [10]. To avoid excessive stiffness for the ODE solver, the acid-base physico-chemical reaction equations have been modeled as an algebraic equation (AE) system ($\boldsymbol{z} \in \mathbb{R}^{30}$), within a **`partial model`** extended to the reactor model (the $\boldsymbol{g}$ function of Eq.1). The latter has a subset of state chemical total components $x_j, j = 1 \dots N_c$ as input and outputs the chemical ionic speciation $S_i, i = 1 \dots N_s$, the pH and the ionic strength I (mol$_{eq}$ L^{-1}) of the liquid mixture, exploiting N_c molar balances (Eq.5), $N_s - N_c$ chemical equilibrium equations, the charge balance over mixture neutrality hypothesis (Eq.6) and the definition of I (Eq.7) [10]; activity corrections γ are computed from the Davies equation (Eq.8):

$$0 = x_j - \sum_{i=1}^{N_s} \upsilon_{i,j} S_i \quad (5)$$

$$0 = \sum_{i=1}^{N_s} z_i^2 S_i^{z_i} - S_{OH^-} + S_{H^+} \quad (6)$$

$$I = \frac{1}{2} \sum_{i=1}^{N_s} z_i^2 S_i^{z_i} \quad (7)$$

$$\log_{10} \gamma = -A z_i^2 \left(\frac{\sqrt{I}}{1+\sqrt{I}} - BI \right) \quad (8)$$

where S_i is a molar concentration (M) of the i^{th} chemical ionic species and z_i its charge, $\upsilon_{i,j}$ are stoichiometric parameters, A and B are solution-specific parameters, S_{OH^-} and S_{H^+} (M) are the molar concentrations of water hydroxide and hydrogen ions. The resulting non-linear algebraic loop was simplified by neglecting ion-pairing reactions, so that the number of residual equations after *tearing* is reduced from $N_c + 1$ down to 2 (I, pH), reducing the dependency of the Newton-Raphson solver on proper start guesses. The consistency of the physico-chemical sub-model extensions and hypothesis was verified by comparison with both results from literature [4] and Visual MINTEQ 3.1.

(c) Copp-like interface

The interface contains algebraic equations intended to redistribute or lump the nutrient contents in the inlet stream to the components of the outlet connector. This is primarily because the two bio-process models are characterized by a different lumping degree of the chemical components that describe the liquid mixture. Consequently, some of them are also characterized by different elemental contents. For example, the biodegradable particulate organic matter concentration X_s (g$_{COD}$ m^{-3}) in ALBA is intended to lump the biodegradable particulate carbohydrates X_{ch} (kg$_{COD}$ m^{-3}), proteins X_{pr}) (kg$_{COD}$ m^{-3}) and lipids X_{li} (kg$_{COD}$ m^{-3}) of agri-AcoDM, as well the biodegradable fraction of the bacterial biomass that does not survive in the RWP:

$$X_s = 10^3 \left[\left(1 - f_{xh,xb} - f_{xnit,xb}\right)\left(1 - f_{xi,xb}\right) \sum_{i=1}^{5} X_{bm_i} + \right.$$
$$\left. + \left(1 - f_{xi,xb}\right) \sum_{i=1}^{2} X_{bm_j} + X_{pr} + X_{ch} + X_{li} \right] \quad (9)$$

where $f_{.,.}$ are portioning parameters, X_{bm_i} and X_{bm_j} (kg$_{COD}$ m^{-3}) are agri-AcoDM facultative aerobic and strictly anaerobic bacterial populations respectively. Any difference in the elemental contents is added/removed from the correspondent dissolved inorganic concentration S_j of element j (C, N, P) to guarantee atomic mass conservation, i.e.:

$$S_j = \sum_{i=1}^{n} x_i \nu_{j,i} - \sum_{k=1}^{m} x_k \nu_{j,k} \quad (10)$$

where n and m are the number of agri-AcoDM and ALBA states restricted to the liquid-solid mixture respectively, and $\nu_{j,i}$ (g$_j$ g$_i^{-1}$) are the stoichiometric fixed parameters that represent the content of element j in the state i

(same holds for k).

(d) Solid-liquid separation units

The screw-press model contains mass balance algebraic equations. Additional equations are used to specify the portioning of each state variable to the two output mass ports, via fixed average removal efficiencies. The flocculation unit contains similar equations, while accounting for the dilution factor introduced by the coagulant dosage.

(e) Thermal sub-models (GPS)

The state variables are the 3 temperatures of the interacting heat capacities and the water vapour content $e_{int,air}$ (kg m_{air}^{-3}) of the greenhouse internal air. The state variables interact with each other via conductive, convective, latent-convective and radiative heat fluxes $\mathbf{\Phi}$ (W). The ODE ($\boldsymbol{x} \in \mathbb{R}^4$) are the energy balances of each uniform layer, i.e.:

$$CV\dot{\boldsymbol{T}} = Q(\boldsymbol{T_{in}} - \boldsymbol{T}) + \mathbf{\Phi}(\mathbf{T}, \boldsymbol{\theta}, \boldsymbol{d}) + \boldsymbol{u} \tag{11}$$

where C (J m^{-3} °C^{-1}) is the volume-specific heat capacity, V (m^3) is the volume, $\boldsymbol{\theta}$ are fixed parameters, $\boldsymbol{d}$ are the external disturbances (i.e. external global irradiance at ground I_0 (W)) and $\boldsymbol{u}$ are the control inputs. The first additive forcing term is related to the enthalpic contributions of inlet/outlet flows of matter Q (m^3 s^{-1}), which are present only for the internal air and RWP water layers. Water mass balance over the greenhouse internal air is used to calculate $e_{int,air}$, which is involved in the latent-convective heat exchange. The cover temperatures are algebraic variables (negligible heat capacity). A MISO conditional PID control is in place on RWP water temperature via both direct heat/cool flux and indirect mechanical ventilation air exchanges as control variables.

(f) Raceway pond (ALBA)

From the hydraulic standpoints, the reactor is an open and completely stirred tank reactor (CSTR) with constant volume. The same acid-base reactions algebraic system described in (b) was extended to this model. The state variables $\boldsymbol{x}$ are 31 concentrations in the specific media of either bacterial aerobic populations, microalgae or organic/inorganic matter total components. Some of the latter are not present in agri-AcoDM and viceversa (e.g. dissolved oxygen S_{O_2}). The state variables interact with each other via biological (hydrolysis, growth, respiration, decay) and the same physico-chemical process rates described in (b). The ODE for the liquid-solid mixture are mass balances similar to the one described in (b), i.e.:

$$\dot{\boldsymbol{x}} = \frac{Q}{V}(\boldsymbol{x_{in}} - \boldsymbol{x}) + \mathbf{K_P}\,\mathbf{r}(\boldsymbol{x}, \boldsymbol{\theta_p}, \boldsymbol{z}, \boldsymbol{d}) \tag{12}$$

where Q (m^3 d^{-1}) is the volumetric flowrate of influent diluted and separated liquid digestate and $\boldsymbol{d}$ are disturbances, mainly external air temperature T (°C) and total solar irradiance at ground (converted to photo-synthetically active radiation (PAR) I_{PAR} (μmol s^{-1})). Matrix $\mathbf{K_P}$ is the transposed stoichiometric Peterson matrix [6] that guarantees COD and atomic mass conservation, extended and modified according to the new variables and processes introduced. The general expression of bioprocess kinetics is similar to the one reported in (b), but additional multiplicative terms related to temperature and PAR dependency are present for microalgae rates. A SISO conditional (upper-bound) P control is performed on raceway pH via CO_2 injection as control variable.

III. MODEL APPLICATION

The following design assumptions and data were used for the biorefinery under study:

- *Location and weather data*. The plant is located in the Northern Italy (Cremona) and local weather data were used to run simulations.
- *Anaerobic co-digester*. A 1-MW plant was considered with two parallel fermenters and a post-fermenter (hydraulic retention time (HRT) = 33 d, 42°C). The plant is fed with cattle slurry (72%$_{ww}$), solid cattle manure (8 %$_{ww}$) and, according to the season, maize silage (October-June) or tomato peels (July-September) (20%$_{ww}$). An average biogas flowrate of approximately 11'000 Nm^3 d^{-1} (CH_4: 51.5%, CO_2: 48.5% v/v) is generated, along with 180 m^3 d^{-1} of raw digestate (6–7 %TS).
- *Digestate S/L separation and pre-treatments*. The liquid fraction of digestate is further separated through screw press and flocculant-assisted centrifugation.
- *Algal cultivation ponds*. A large-scale system (surface 7'560 m^2, liquid height 20 cm, HRT = 5 d) was designed to grow a *Chlorella-Scenedesmus* consortium. In the latter, pH is controlled to remain below 7.5, whereas temperature is not.

The flexibility and applicability of the model was tested in an open loop scenario analysis (Table 1) to verify the process feasibility in terms of microalgae biomass harvesting rates, when forcing the system with different agri-AcoD influent diet (e.g. slurry/maize ratio) and design (e.g. HRT) and thermal boundary conditions (e.g. number of greenhouse's covers). The DASSL solver [11], an implicit, gradient-based, integration algorithm with variable step size (suitable for stiff systems) was selected for the numerical resolution of the DAE system.

IV. RESULTS AND DISCUSSIONS

The verification of the consistency of the physico-chemical sub-model hypothesis returned relative mean

Table 1: Open-loop scenarios studied for the case-study of interest.

Scenario ID	Scope	HRT (d)	Silage-tomato load (ton d^{-1})	Cow slurry load (ton d^{-1})	Greenhouse cover
S.1.1.1-O	Baseline	33	37	130	Open
S.2.1.1-O	Effect of AcoD operative conditions	66	37	130	Open
S.1.2.2-O		33	67	100	Open
S.2.2.2-O		66	67	100	Open
S.1.1.1-1C	Effect of microalgae cultivation configuration	33	37	130	One-cover
S.1.1.1-2C		33	37	130	Two-covers

errors (RMEs) of 0.04% and 0.4% for the prediction of the digester pH (7.5) and I (0.25 mol$_{eq}$ L^{-1}) respectively. It is worth noticing that the low RMEs obtained in this case-study were likely due to the low contribution of water hardness components (dissolved calcium S_{ca} and magnesium S_{mg}) to the overall I, that was mainly composed by the other dissolved inorganics (P (S_{ip}), N (S_{in}), C S_{ic})), and cations (dissolved potassium (S_K)).
This holds specifically for agro-zootechnical co-feedstocks, whereas this simplified approach that neglects ion-pairing reactions may lead to higher RMEs with other type of AcoD influent compositions.

The simulation of the biorefinery allowed to evaluate the quality of the liquid digestate produced and its suitability to be fed to the algal cultivation unit. Precipitation was quite severe in the agri-AcoD unit (66% of outflow inorganic P is precipitated) due to the high presence of free carbonate (CO_3^{2-}) and ammonia (NH_3) ions, and the main precipitated salts were struvite (X_{stru} 9.2 mol m^{-3}) and calcite (X_{ccm}, 5 mol m^{-3}). Amorphous calcium phosphate (X_{acp}) precipitation was hindered by the high average N/P ratio (5.7$_{w/w}$) of this type of digestate. Indeed, a relevant portion of the total inorganic P is removed ($\approx$ 80%) during flocculation along with coagulated solids, so that the nutrient load reaching the RWP cannot be fully exploited. Nonetheless, the incoming salt seeding material tends to redissolve in the RWP thanks to microalgae inorganic dissolved C and N uptake, guaranteeing a 'stock' of nutrients that becomes available to microorganism under proper pH and I conditions. Figure 2a depicts the trend of algal concentration for the four different agri-AcoD scenarios. The best performance in terms of algal biomass production was observed during spring for the scenario with an increased co-digester HRT and unchanged feeding strategy (S.2.1.1-O). This can be primarily accountable to the higher S_{ip} concentration in the liquid digestate that leads to a lower microalgal P limitation, thanks to (i) the higher content of influent S_{ip} in cow slurry and (ii) a longer residence time in the co-digester that allows a higher extent of lipids' hydrolysis. During summer, the feeding of tomato peels to the agri-AcoD unit features a lower volatile solid and a higher lipid content with respect to maize silage, so that it leads to (i) a 6% higher biogas methane content, (ii) a 12% lower biogas flowrate and (iii) an increase in the effluent S_{ip} up to a peak 70% and 35% on average. Due to the slow dynamics of this state variable, sufficient nutrient availability was provided in autumn, resulting in a narrower difference between scenarios. The concentration of aerobic bacteria was higher for the scenarios S.1.2.2-O and S.2.2.2-O, mostly due to the increased undegraded organic matter load coming from the co-digester. This, in turn, would determine lower CO_2 injection rates to perform pH control, but lower 'pureness' of the outflow biomass product. The yearly productivity was estimated to be 54 ton$_{DM}$ y^{-1} (19 g$_{DM}$ m^{-2} d^{-1}, 78% of microalgae over total microorganism concentration, which are values in line with experimental literature) for the baseline scenario (S.1.1.1-O).

The effect of greenhouse covering in the RWP configuration is shown in Figure 3. Although a greenhouse ensures higher productivity during winter compared to open ponds, excessive covering (S.1.1.1-2C) can lead to strong overheat during summer and resulting in culture breakdown (-60% yearly average productivity). This outcome depends on the plant's latitude (weather data) and on the algal thermal response's $\boldsymbol{\theta_p}$. The summer productivity was more sensitive to temperature variations, while the productivity in winter was mainly limited by low I_{PAR}.

V. CONCLUSIONS AND FUTURE WORK

The scenario analysis improved process understanding through a preliminary assessment of the impact of co-digester design and feeding strategy on digestate properties and microalgae production, with particular focus on the risk of algal P limitations due to precipitation. Results highlighted the importance of properly designing the whole biorefinery, and yet a noteworthy robustness of the microalgae cultivation's performance: however, it can be strongly affected by the presence of greenhouse covers on the RWP. It is remarked that the overall **bio-refinery** model has not been validated yet, due to the lack of data, but that each major sub-model was extensively validated in previous works, proving its reliability. Nevertheless, the fine-tuning of the uncertain biological kinetic parameters and an overall validation over real

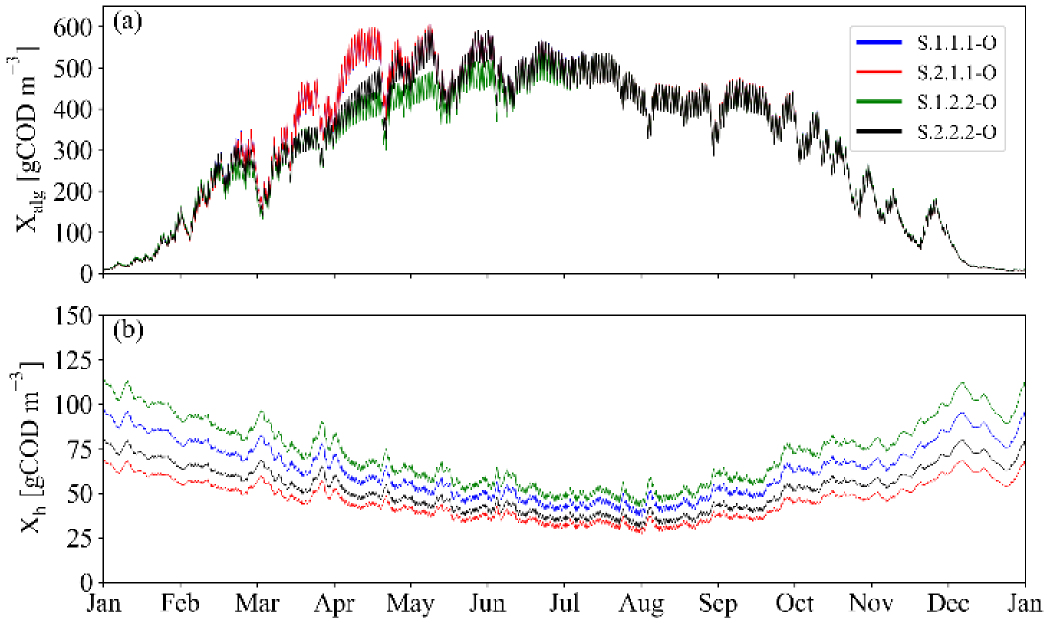

Figure 2: Simulation results: (a) yearly microalgae (X_{alg}) and (b) aerobic bacteria (X_h) concentrations for different scenario (AcoD operative conditions).

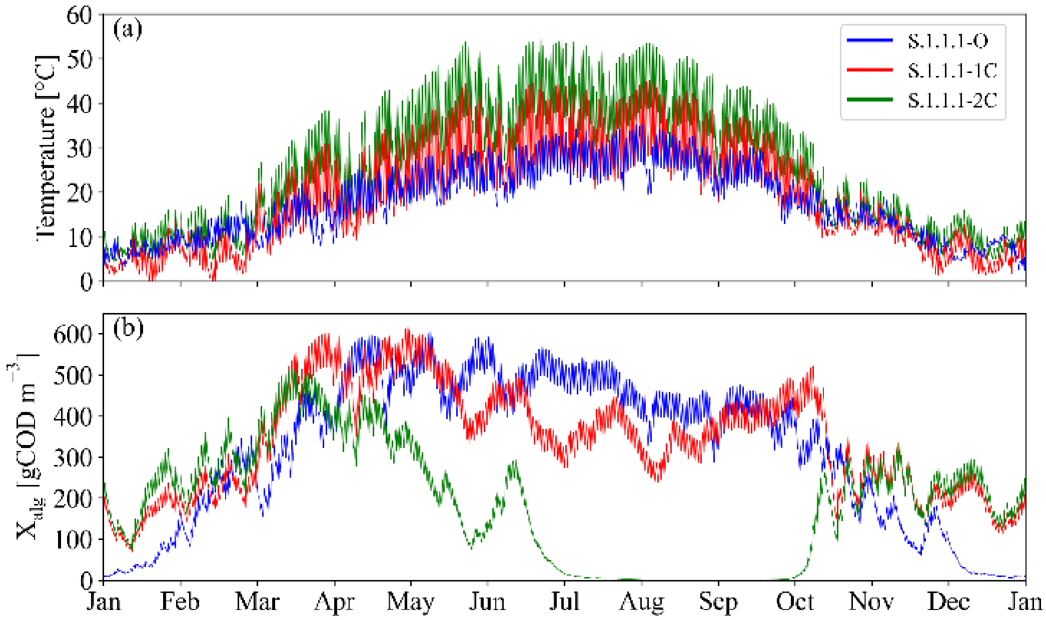

Figure 3: Simulation results: (a) RWP's water temperature and (b) yearly microalgae (X_{alg}) concentration for the different scenario (GPS-RWP thermal configurations).

data for the specific case of study will be required. Afterwards, the model could be exploited for the optimal techno-economic design of the process and as a high-fidelity '*real plant*' to validate classical/advanced control schemes, in support of the technology's scale-up. It is remarked that feedback control loops over the whole plant would require the frequent (e.g. 1 d^{-1})/automatic measurement of the inorganic nutrients (mainly P, N), that is far from being cost-effectively applicable, especially for anaerobic digesters. Further insights on the modeling of S/L separation units will be required too. Yet, the model could serve, for example, (i) to assess the cost-effectiveness of heating/cooling inputs to boost microalgae productivity, and (ii) the validation of control schemes with bioreactors' HRTs/BRTs as $\boldsymbol{u}$ and revenues from biomethane and microalgae production as $\boldsymbol{y}$. Eventually, the aim of this work was to open novel discussions for the implementation of biorefineries' plant-wide models.

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REFERENCES

1. C. Vaneeckhaute, F. Claeys, F. Tack, E. Meers, E. Belia, and P. Vanrolleghem, "Development, implementation, and validation of a generic nutrient recovery model (NRM) library," Environmental Modelling & Software, vol. 99, pp. 170–209, 2018.
2. D. Batstone et al., "The IWA Anaerobic Digestion Model No 1 (ADM1)," Water Science and Technology, vol. 45, no. 10, pp. 65–73, 05 2002. https://doi.org/10.2166/wst.2002.0292
3. A. Catenacci, M. Grana, F. Malpei, and E. Ficara, "Optimizing ADM1 calibration and input characterization for effective co-digestion modelling," Water, vol. 13, no. 21, 2021.
4. X. Flores-Alsina et al., "Modelling phosphorus (P), sulfur (S) and iron (Fe) interactions for dynamic simulations of anaerobic digestion processes," Water Research, vol. 95, pp. 370–382, 2016. https://doi.org/10.1016/j.watres.2016.03.012
5. K. Bułkowska, I. Białobrzewski, E. Klimiuk, and T. Pokój, "Kinetic parameters of volatile fatty acids uptake in the adm1 as key factors for modeling co-digestion of silages with pig manure, thin stillage and glycerine phase," Renewable Energy, vol. 126, pp. 163–176, 2018.
6. F. Casagli, G. Zuccaro, O. Bernard, J.-P. Steyer, and E. Ficara, "ALBA: A comprehensive growth model to optimize algae-bacteria wastewater treatment in raceway ponds," Water Research, vol. 190, p. 116734, 2021.
7. S. Li, D. H. Willits, C. L. Browdy, M. B. Timmons, and T. M. Losordo, "Thermal modeling of greenhouse aquaculture raceway systems," Aquacultural Engineering, vol. 41, no. 1, pp. 1–13, 2009.
8. P. Fritzson et al., "The OpenModelica Integrated Environment for Modeling, Simulation, and Model-Based Development," Modeling, Identification and Control: A Norwegian Research Bulletin, vol. 41, pp. 241–295, 10 2020. https://doi.org/10.4173/mic.2020.4.1
9. S. Weinrich & M. Nelles, "Systematic simplification of the Anaerobic Digestion Model No. 1 (ADM1) – Model development and stoichiometric analysis," Bioresource Technology, vol. 333, p. 125124, 2021.
10. D. Batstone and X. Flores-Alsina, Generalized Physicochemical Model (PCM) for Wastewater Processes. IWA Publishing, 11 2022.
11. L. R. Petzold, "Description of DASSL: a differential/algebraic system solver," 9 1982.