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Ex-ante LCA for circular resource management of liquid digestate, by predictive modeling of algae-bacterial processes

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Abstract

The simplest method for treating liquid digestate, which involves directly spreading it over local agricultural land, is facing scrutiny due to the challenges of transporting large volumes and the environmental risks posed by nitrogen and phosphorus pollutants. Improvements in liquid digestate treatment are necessary to mitigate these threats and support a growing circular economy. This study evaluates an advanced digestate treatment method that decouples hydraulic retention time (HRT) and solid retention time (SRT) in high-rate algal/bacterial ponds (HRABPs). By combining life cycle assessment (LCA) with high-fidelity modeling for HRABPs, this study simulates productivity and removal efficiencies under realistic climatological conditions, providing life cycle inventories for numerous large-scale scenarios. To minimize environmental impacts while maximizing algal productivity and nitrogen intake in the algal biomass, 36 scenarios were simulated, considering different HRT, SRT, alkalinity addition, winter storage, and biomass post-treatment hypotheses. The results demonstrate that microalgae treatment makes sense for valorizing liquid digestate, proving to be less impactful than direct land application. However, the LCA results also highlight the complexity of the issue. Low HRT (HRT = 5 days < SRT = 10 days), including winter storage, requires the smallest production area, resulting in high productivity and low environmental impacts. Conversely, high HRT (HRT = 90 days > SRT = 15 days) achieves the highest efficiency in nitrogen and phosphorus recycling but necessitates large production areas, leading to high environmental impacts. Mathematical modeling, coupled with LCA, can resolve these trade-offs and guide the optimization and scaling-up of climatology-dependent systems.

KEYWORDS

bioenergy, circular economy, high-rate algae ponds, microalgae, nitrogen balance, wastewater treatment

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1 | INTRODUCTION

The concept of sustainable wastewater management broadly involves the efficient treatment and reutilization of wastewater and its related emissions in a sustainable manner (Meena et al., 2019). The current wastewater treatment plants (WWTPs) are gradually identified as a reservoir of resources for nutrient recycling and the generation of added-value products (Singh et al., 2023). From a circular economy perspective, WWTPs are not only useful for pollution removal but also represent factories producing reusable water and added-value resources (Colella et al., 2021). The European Commission defines the circular bioeconomy strategy as the “production of renewable biological resources and the conversion of these resources and waste streams into added-value products, such as food, feed, bio-based products and bioenergy” (European Environment Agency, 2012). Establishing circular economy management in the wastewater sector for more sustainable practices can alleviate water scarcity and generate additional revenue (Colella et al., 2021).

Digestate is an important byproduct of WWTPs consisting of solid (10%–20% by mass) and liquid (80%–90% by mass) fractions (Fuchs & Drogg, 2013). Solid digestate is more stable, easily transported, and stored and can be used as an agricultural bio-fertilizer or further converted to heat and/or added-value products via thermal processes (Fuchs & Drogg, 2013; Monlau et al., 2015). However, liquid digestate processing is more complex. The simplest treatment method is to directly spread over local agricultural land, which may cause eutrophication of nearby water systems due to NH_3 and N_2O emissions to the atmosphere (Levine et al., 2011), or reduce the long-term crop productivity of soil due to contamination, for example, plastics, heavy metals or pathogens (Nkoa, 2014). Partially or untreated wastewater containing excess phosphorous and ammonia might cause disruptions in the aquatic ecological balance, such as eutrophication or oxygen depletion in the receiving water bodies, and increased GHGs emissions (Kathi et al., 2023). WWTPs are designed to treat wastewater to maintain the water quality standard at an appropriate level, before releasing it into the environment (Bora et al., 2020). In Europe, the Urban Wastewater Treatment Directive (UWTD) sets effluent discharge limits for total phosphorus (TP) at 1 (or 2 mg/L) and total nitrogen (TN) at 10 (or 15 mg/L) for larger than 100,000 population equivalent (PE) or, lower than 100,000 PE, respectively (European Commission, 2016).

An integrated system involving wastewater treatment, CO_2 sequestration, and added-value products is the new aspiration of wastewater management (Verma et al., 2021). In recent years, microalgae have received increased interest in being included, together with bacteria, in the wastewater treatment process, based on their ability to consume organic and inorganic carbon, as well as inorganic nitrogen (N) and phosphorous (P) (Thanigaivel et al., 2022). The ubiquity of algae adapted to every climate, their high growth rate, and their ability to convert CO_2 into organic molecules that can be turned into added-value products, contribute to their potential use (Thanigaivel et al., 2022). Their high nutrient removal efficiency in advanced urban, agricultural, and industrial wastewater treatment has paved the way for improved tertiary wastewater treatment (Rout et al., 2022). Recycling biogenic carbon, N, and P can potentially reduce GHG emissions compared to conventional wastewater treatment processes (Mat Aron et al., 2020).

The addition of a separation system, such as membrane modules after microalgae cultivation, has been shown to be a technological breakthrough (González-Camejo et al., 2019; Solmaz & Işık, 2019; Valigore et al., 2012). Depending on the system setup, uncoupling of hydraulic retention time (HRT) and solid retention time (SRT) can allow a continuous biomass extraction of the system at a rate larger than the dilution rate ($\text{SRT} < \text{HRT}$), or an accumulation of the biomass in the reactor ($\text{SRT} > \text{HRT}$). This can be effectively achieved in practice through a membrane-based separation system, either integrated directly into the reactor or placed in a separate module downstream of the reactor. In these configurations, the liquid and solid phases are separated, with one phase being recirculated depending on the desired outcome: To increase the HRT, the liquid phase is recirculated into the reactor, whereas to increase the SRT, the solid fraction is recirculated. Separation systems have demonstrated considerable enhancement of the overall process efficiency, leading to a twofold increase in microalgal productivity or N recycling efficiency (Casagli et al., 2023), directly reducing the process footprint (Barbera et al., 2020). This further justifies the use of liquid digestate for microalgae cultivation (Casagli et al., 2023) and the recycling of the microalgal biomass as a feedstock for the manufacture of different products, such as bioplastics (biopolymers), biofuels, and bioactive compounds. Numerous life cycle assessment (LCA) studies have been published evaluating the potential of microalgae-based treatment for liquid digestate (Arashiro et al., 2018, 2022). However, only a few studies account for the actual variability of microalgal metabolism experimentally observed because of operational strategies and meteorological fluctuations (Morales et al., 2019; Pérez-López et al., 2017). The question of whether environmental benefits are compromised by the operational strategies used to grow microalgae across different seasons has hardly been studied so far. Here, we compare this approach with the conventional approach for liquid digestate valorization by land spreading. The main objective of the study is to measure, through LCA, the environmental impacts of microalgae–bacteria system for the treatment of liquid digestate. This study evaluates the recycling of nutrients (N and P) and water from liquid digestate feeding a high rate algal/bacterial pond (HRABP), thus reducing the discharge to the natural environment, while producing microalgae. In the spirit of *ex ante* LCA, where the inventory of the main flows to and from the environment cannot be measured directly from an existing industrial process but must be extrapolated, we use high-fidelity modeling for HRABP (Casagli et al., 2021, 2023). Fluxes and productivities of a large-scale plant located in Rennes (France) are then simulated under a realistic climate (Casagli & Bernard, 2022).

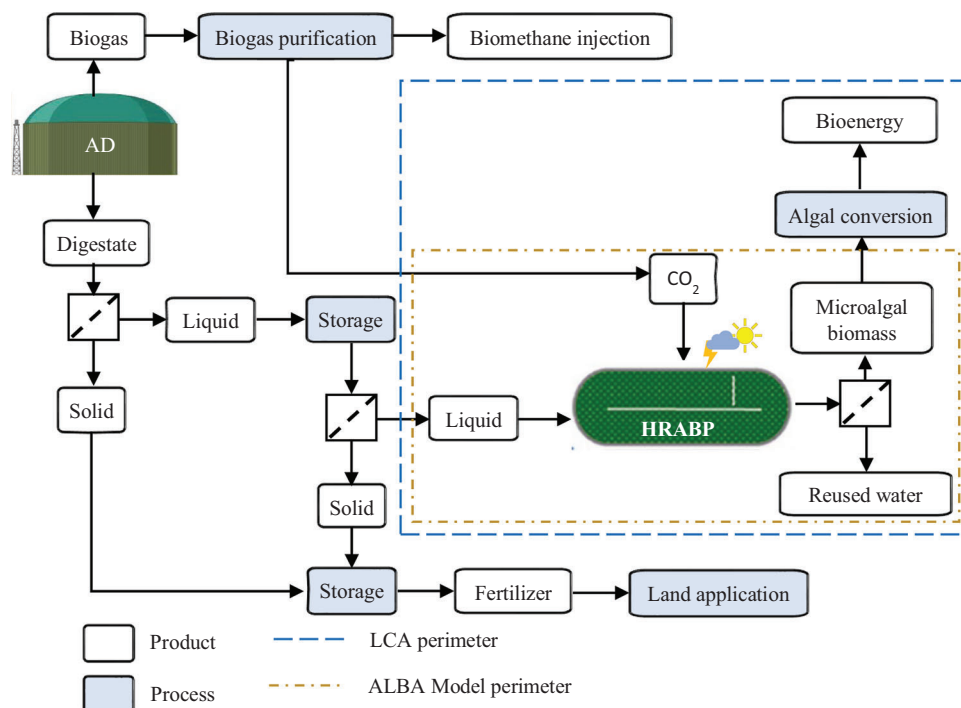


FIGURE 1 Life cycle assessment (LCA) and mathematical model conceptual frameworks used to assess microalgae cultivation for liquid digestate treatment and valorization. ALBA, ALgae–Bacteria; HRABP, high-rate algal/bacterial pond.

2 | METHODS

2.1 | Study goal and scope definition

This study explores a circular economy approach to microalgae cultivation and liquid digestate treatment, recycling nutrients (N, P, and CO₂), and water from anaerobic digestion of agricultural waste, reducing environmental discharge, and producing microalgae-based bioenergy products (bioelectricity, gasoline, and biodiesel).

The concept of microalgal cultivation combined with biogas production (where the by-product CO₂ is used for microalgae growth) is illustrated in Figure 1. This approach involves the simultaneous removal of nutrients from liquid digestate and CO₂ fixation through microalgal biomass accumulation. The microalgal biomass generated in this process can be seamlessly integrated into a biorefinery, thereby enhancing economic feasibility and facilitating energy recovery. The main objective of the study is to assess the environmental performance of this process before it is scaled up. We develop an ex ante LCA methodology (perimeter of the study shown in blue in Figure 1 and detailed in Section 2.2) supported by a mathematical model to compute the fluxes along the year (perimeter shown in brown in Figure 1) necessary for the inventory, and eventually the resulting environmental impacts of treating liquid digestate by a microalgae-based system.

LCA was conducted following ISO standards (ISO 14040, 2006; ISO 14044, 2006), and a robust long-term validated model for HRABPs (Casagli et al., 2021) was used to simulate and optimize a large-scale system treating digestates to maximize algal productivity and/or the nitrogen fraction intake in the algal biomass, thus reducing environmental burdens. This study determines the effects of operational parameters, SRT and HRT, pH, and medium recycling on a microalgae biomass pond area, according to seasonal removal efficiency of nutrients (N and P) and CO₂ fixation rates, on the subsequent environmental burdens. The liquid digestate (22,155 tonnes/year) is collected from an anaerobic digestion unit located in Brittany Region (France) and treating 25,000 tonnes of agricultural residue per year. The biogas and biomethane production of this unit are 123 and 74 Nm³/h, respectively. Such biomethane production is close to the average production of agricultural biogas units in Brittany estimated to be 78 Nm³/h in 2021 (DREAL Bretagne, 2021). The methane is purified for injection into the natural gas network, and this produces “available” CO₂ of around 1060 Nm³/day, as shown in Figure 1. The liquid digestate used in this study corresponds to a typical liquid fraction issued from a centrifuge decanter separation of agricultural digestate as detailed in Table 1 of Supporting Information S1.

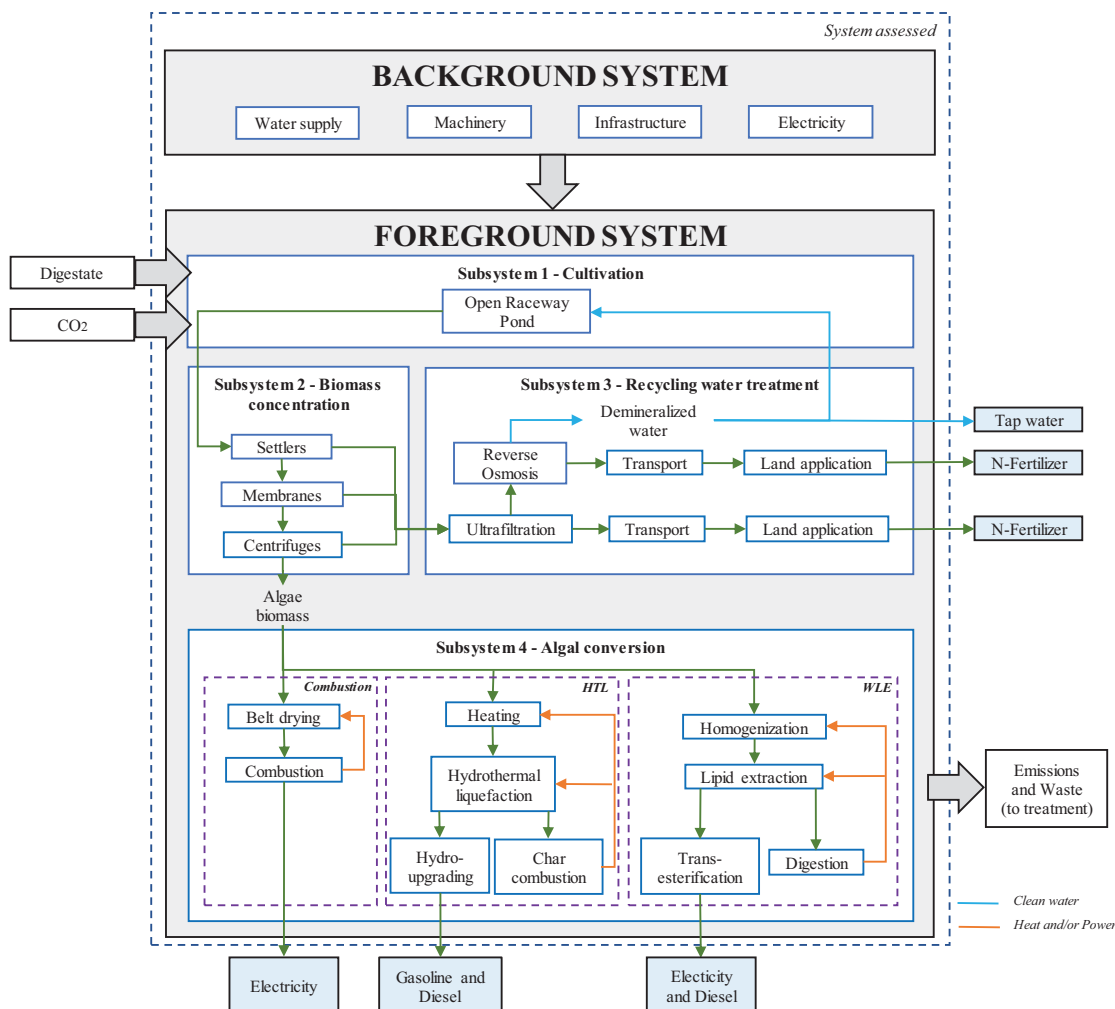


FIGURE 2 System boundaries. Main stages of the biorefinery approach of microalgae cultivation for liquid digestate valorization and treatment with the three scenarios of energetic algal conversion.

2.2 | System boundary and functional unit

A pond-to-gate attributional LCA is performed. These boundaries include the infrastructure, machinery production, emissions, and transport related to the chemicals and materials used in the foreground process systems. The dismantling and final disposal of machinery and infrastructure materials completed the background system, based on data from the ecoinvent v3.10 database. Figure 2 shows the life cycle boundaries and the four considered subsystems: subsystem 1—cultivation, subsystem 2—biomass concentration, subsystem 3—recycling water treatment, and subsystem 4—algal conversion. Details on these subsystems are provided in Section 2 of Supporting Information S1. The functional unit (FU) is defined as 1 m³ of treated effluent (diluted liquid digestate), in line with most studies relating to wastewater management that use volume units of treated wastewater as FU (Corominas et al., 2013). The substitution method (Provost-Savar & Majeau-Bettez, 2024) used to address the co-products (e.g., tap water, N-fertilizer, gasoline, diesel, and electricity) across the different scenarios is assumed to include credits for avoided burdens, as detailed in Section 2 of Supporting Information S1.

2.3 | Mathematical model: Structure and integration with LCA

The ALBA (ALgae-BACteria) model (Casagli et al., 2021) is a comprehensive mathematical tool for characterizing the algae–bacteria ecosystem. Specifically designed for HRABP, the model simulates algal–bacterial interactions from a wastewater treatment perspective. It analyzes bioremediation performances and enhances our comprehension of the interplay between chemical, physical, and biological processes. The biological

model incorporates a mixed consortium of photoautotrophic algae, heterotrophic bacteria, ammonia-oxidizing bacteria (AOB), and nitrite-oxidizing bacteria (NOB).

These model-derived insights played a pivotal role in the LCA methodology to provide the mass and energy balance within subsystem 1 (Section 3 of Supporting Information S1). Using simulated data from the ALBA model, input and output flows for cultivation ponds were computed, encompassing pond emissions (e.g., N_2O and NH_3), N and P balances, biomass productivity, and other relevant parameters. For a more comprehensive description of the ALBA model, including its structure, calibration, and validation procedures, we invite the reader to refer to Casagli et al. (2021, 2021b, 2022b) and Nordio et al. (2025). Moreover, a comprehensive description of the ALBA model and how N_2O production and emissions were integrated into the ALBA model to assess the N_2O fluxes are reported in Sections 4 and 5 of Supporting Information S1.

2.4 | Life cycle inventory and scenario definition

The inventory relies on two main inputs constraining the process (liquid digestate and CO_2). Two hypotheses for managing liquid digestate are considered, depending on whether or not HRABP is assumed to be stopped during winter, which necessitates winter storage. Liquid volumes digestate fluctuate along the year, requiring a variable energy consumption from the French matrix network. It is assumed that the N and P content in the digestate covers the demand of the microalgae. NaOH is added to adjust alkalinity, depending on the scenario.

The parameters HRT, SRT, pH setpoint, and winter storage, have been shown to be instrumental in improving algal biomass productivity and nutrient outputs (Casagli et al., 2023; Casagli et al., 2021). On top of these primary scenarios, three possible down-processing options are assessed for algal-to-energy conversion pathways, combustion, hydrothermal liquefaction (HTL), and wet liquid extraction (WLE) (as detailed in Section 2.4 of Supporting Information S1).

2.4.1 | HRT and SRT

Simulations were run considering that HRT and SRT could be independently tuned, therefore, simulating two cases with HRT larger than SRT, that is, liquid recirculated in the reactor, while biomass is withdrawn from the system and, reversely, for HRT lower than SRT, that is, where a fraction of the recovered concentrated biomass (from subsystem 2) is recycled back into the HRABP. To ease the presentation, each scenario will be characterized by the couple (HRT, SRT). For example, the scenario (HRT90, SRT15) stands for HRT of 90 days and SRT of 15 days.

A first numerical exploration was carried out, inspired by Casagli et al. (2023), where a wide range of HRT, SRT, liquid depth, and total alkalinity conditions were explored, in order to maximize algal biomass productivity, nitrogen recycling, and minimizing N_2O emission. Scenarios with HRT or SRT lower than 5 days were not considered, given the very low or totally absent nitrifying activity under these suboptimal operational conditions with the chosen climatology for AOB and NOB growth.

Three scenarios reaching optimal values for one of the considered performance criteria were retained:

- (i) $HRT \gg SRT$, this condition considers (HRT90, SRT15).
- (ii) $HRT > SRT$, for (HRT10, SRT5)
- (iii) $HRT < SRT$, for (HRT5, SRT10).

The corresponding reactor volume (V_R , m^3) in the plant is calculated to process the HRABP influent flow rate (Q_{in} , equal to 405.6 or 303.4 m^3/day , depending on the inclusion or not of winter storage).

$$V_R = HRT \cdot Q_{in} \quad (1)$$

where the input flow (Q_{in} , m^3/day) is defined as Equation (2):

$$Q_{in} = (R + 1) \cdot Q_i \quad (2)$$

Here, R is the recycle ratio, defined as a dimensionless operating variable to account for the ratio of the recycled flow (m^3/day). R is fixed as 4 for all scenarios; and Q_i is the inlet volumetric flow rate of digestate, equal to 81.11 or 60.67 m^3/day depending on the inclusion, or not, of winter storage (i.e., the production plant turns off during winter months), respectively. The production area (area, m^2) is then defined as Equation (3), where h (in

m, 0.3 m) is the depth of the HARBPs.

$$\text{Area} = \frac{\text{HRT} \cdot Q_{\text{in}}}{h} \quad (3)$$

The production area (in m²) required for microalgae cultivation increases if the algae plant is active only a fraction of the year (with winter storage) to process the same overall digestate over a smaller period. The production areas with winter storage are 18.2, 2.03, and 1.01 ha for HRT of 90, 10, and 5 days, respectively. When operated all the year, the production area decreases by 25% down to 13.6, 1.51, and 0.76 ha for HRT of 90, 10, and 5 days, respectively.

We assume that the treatment plant consisted of HRABPs modules of 0.917 ha for the scenarios where HRT was higher than SRT and 0.759 ha for the other scenarios. We therefore considered 20, 2, and 1 pond units for the scenarios with winter storage and 15, 2, and 1 units for the scenarios without winter storage for HRT of 90, 10, and 5 days, respectively. The variation in the number of HRABP units directly affects the required pond materials and the operational energetic demands. Therefore, higher environmental burdens are expected for larger production areas.

2.4.2 | pH and winter storage

pH has an influence on N-emissions (Casagli et al., 2021). At higher alkalinity, a larger amount of inorganic carbon can be stored in the medium, thus providing favorable conditions for algae and nitrifiers, and avoiding N₂O emissions (Casagli et al., 2023). Nevertheless, higher alkalinity is associated with higher pH, driving the equilibrium of ammonium ions (NH₄⁺) toward ammonia (NH₃), thereby allowing more ammonia gas, to be stripped out from the culture into the atmosphere (Chan et al., 2014). Biological activities, driven by environmental (e.g., temperature, light, etc.) and technical (effluent organic matter load, carbon fixation rates, etc.) factors can change pH levels. In some scenarios, this parameter is assumed to be regulated through the addition of NaOH at a concentration of 15.11 g NaOH/m²/day. Finally, the input flow of digestate depends on the considered activity period of the plant. Indeed, if the process is stopped during winter, storage is necessary and Q_{in} for the rest of the time must be increased from 60.67 to 81.11 m³/day, to process the yearly produced digestate. Winter storage prevents the plant from operating during cold months when algal biomass productivity is low. The set of scenarios is thus influenced by hypothetical winter storage and alkalinity addition, as shown in Section 6 of Supporting Information S1.

2.5 | Efficiency of nitrogen and phosphorous recovery

For each scenario, simulations were run with the ALBA model computing the C, N, and P flow rates, under the considered climatology of Rennes, considering the influence of HRT (90; 15; 5 days), SRT (15; 5; 10), alkalinity, and winter storage (yes/no). The different forms of N and P considered in the mass balance of the input flows (gN/m³), in the liquid digestate, and of the outflows (in gN/m³) are detailed in Table 1. The output flows consider the emissions to the atmosphere (stripped out from the cultivation process), the dissolved N and P in the released liquid solution, and the ones harvested in the microalgal–bacterial biomass (referred to as output in biomass in Table 1). The values relating to the N and P content in each flow corresponding to subsystems 1 and 2 are shown in Table 3 of Supporting Information S2. The removal efficiency of N (*Eff_N*, *RECYC*, in %) and P (*Eff_P*, *RECYC*, in %) due to microalgae are calculated using Equation (I) provided in Section 7 of Supporting Information S1:

2.6 | Life cycle impact assessment

LCA modeling was carried out in SimaPro software with ReCiPe v1.05 method (H), at the midpoint and endpoint levels. The ReCiPe method includes 17 midpoint impact categories grouped into three endpoint categories as shown in Section 8 of Supporting Information S1, derived from a mid-to-endpoint factor (see factors in Section 9 of Supporting Information S1). The three endpoint categories were considered for ranking the environmental performance of each scenario, also considering productivity, production area, and nitrogen removal efficiency. To benchmark the best scenario for algae–bacteria treatment with the baseline scenario (spreading untreated digestate on agricultural lands), we focus on the following midpoint categories: GW, TA, ME, FE, PM, HH cancer, HH non cancer, FRS, and MRS.

2.7 | Comparison with the baseline cases

The baseline case describes the raw liquid digestate directly spread, without post-treatment, on local agricultural soil surrounding the anaerobic digestion plant. This scenario is one of the most common practices to manage the liquid digestate. It assumes a 10-km transport distance, but other

TABLE 1 Parameter definition in the N and P balance.

Flow	Parameter	Definition
Input in digestate	S_NH_NH ₄	Total ammoniacal nitrogen (TAN) in solution in gN/m ³ : sum at the equilibrium of NH ₃ and NH ₄ ⁺
	S_ND _{org}	Organic nitrogen in solution in gN/m ³
	N_Organic matter	Sum of particulate organic matter (inert particulate organic matter and slowly biodegradable organic matter) and soluble organic matter (readily biodegradable organic matter and inert soluble organic matter) in gN/m ³
	P_Organic matter	Sum of particulate organic matter (inert particulate organic matter and slowly biodegradable organic matter) and soluble organic matter (readily biodegradable organic matter and inert soluble organic matter) in gP/m ³
	S_PO ₄	Total inorganic phosphorus: sum at the equilibrium of PO ₄ ³⁻ , HPO ₄ ²⁻ , H ₂ PO ₄ ⁻ , H ₃ PO ₄ , in gP/m ³
Output to atmosphere	N ₂ O _{atm}	Dinitrogen oxide released to the atmosphere in gN/m ³
	NH ₃ _{atm}	Ammonia released to the atmosphere in gN/m ³
Output in liquid solution	S_NO ₂	Nitrous nitrogen in solution in gN/m ³ : sum at the equilibrium of NO ₂ ⁻ , HNO ₂
	S_NO ₃	Nitric nitrogen in solution in gN/m ³ : sum at the equilibrium of NO ₃ ⁻ , HNO ₃
	S_N ₂	Nitrogen gas in gN/m ³
	S_NH_NH ₄	
	S_ND _{org}	
Output in biomass	N_BM_ALG	Nitrogen harvested in the phototrophic algae in gN/m ³
	N_BM_BAC	Sum of nitrogen in heterotrophic bacteria, ammonia-oxidizing bacteria, and nitrite-oxidizing bacteria, in gN/m ³
	P_BM_ALG	Phosphorus in phototrophic algae in gP/m ³
	P_BM_BAC	Sum of heterotrophic bacteria, ammonia-oxidizing bacteria, and nitrite-oxidizing bacteria, in gP/m ³

distances are evaluated in the LCA analysis in Section 10 of Supporting Information S1. The spreading of the liquid digestate is modeled to be carried out using an agricultural tractor and trailer, with associated emissions based on the work of Angouria-Tsorochidou et al. (2022).

3 | RESULTS AND DISCUSSION

3.1 | Productivity and removal efficiency

The season-dependent and annual average microalgae biomass productivities are shown in Figure 3a (underlying data for Figure 3 are available in Table 6 of Supporting Information S2). Overall, the lowest biomass productivity (from 1.7 to 3.9 g/m²/day) is obtained for the scenarios with HRT of 90 days and SRT of 15 days. The highest annual average productivity ranges from 7.9 to 10.15 g/m²/day and is obtained for HRT of 5 days and SRT of 10 days. The highest microalgae productivity was obtained with alkalinity addition. These results are in line with other studies testing uncoupling HRT and SRT in outdoor algae–bacteria systems for wastewater treatment (González-Camejo et al., 2019; Morillas-España et al., 2021). Productivity during winter (from 0.6 to 3.6 g/m²/day) stays much lower than in summer (2.4–13.3 g/m²/day) or spring (1.9–12.4 g/m²/day). Peaks of 13.3 g/m²/day were reached at (HRT10, SRT5) during summer.

Alkalinity affects biomass productivity since it directly affects the speciation of soluble compounds, such as inorganic carbon, nitrogen, and phosphorus (Casagli et al., 2021). Adding alkalinity to the microalgae cultivation maximizes productivity and minimizes the risk of N₂O emissions. N₂O is a GHG and ozone-depleting pollutant (Plouviez & Guieysse, 2020) emitted via microalgae nitrification and/or denitrification (Plouviez, Shilton et al., 2019). At low alkalinity, inorganic carbon can no longer be stored in the medium and becomes limiting both for algae and nitrifiers, leading to conditions favorable to emissions in the form of N₂O. The ALBA model is therefore a powerful validated tool to assess the algal biomass productivity, the N and P removal rate, but also the risk of highly impacting N₂O emissions. The maximum N₂O emissions (1 × 10⁻³ kg N-N₂O/day) were obtained for HRT larger than SRT, as opposed to the scenarios where HRT was lower than SRT and where N₂O emissions stayed low regardless of the alkalinity addition (7 × 10⁻⁵ kg N-N₂O·d⁻¹) (details in Table 3 of Supporting Information S2). N₂O emissions reached a maximum of 0.001% of the influent N loads, during summer for an HRT of 90 days (scenario 7). For comparison, emissions representing between 0.13% and 0.57% of the

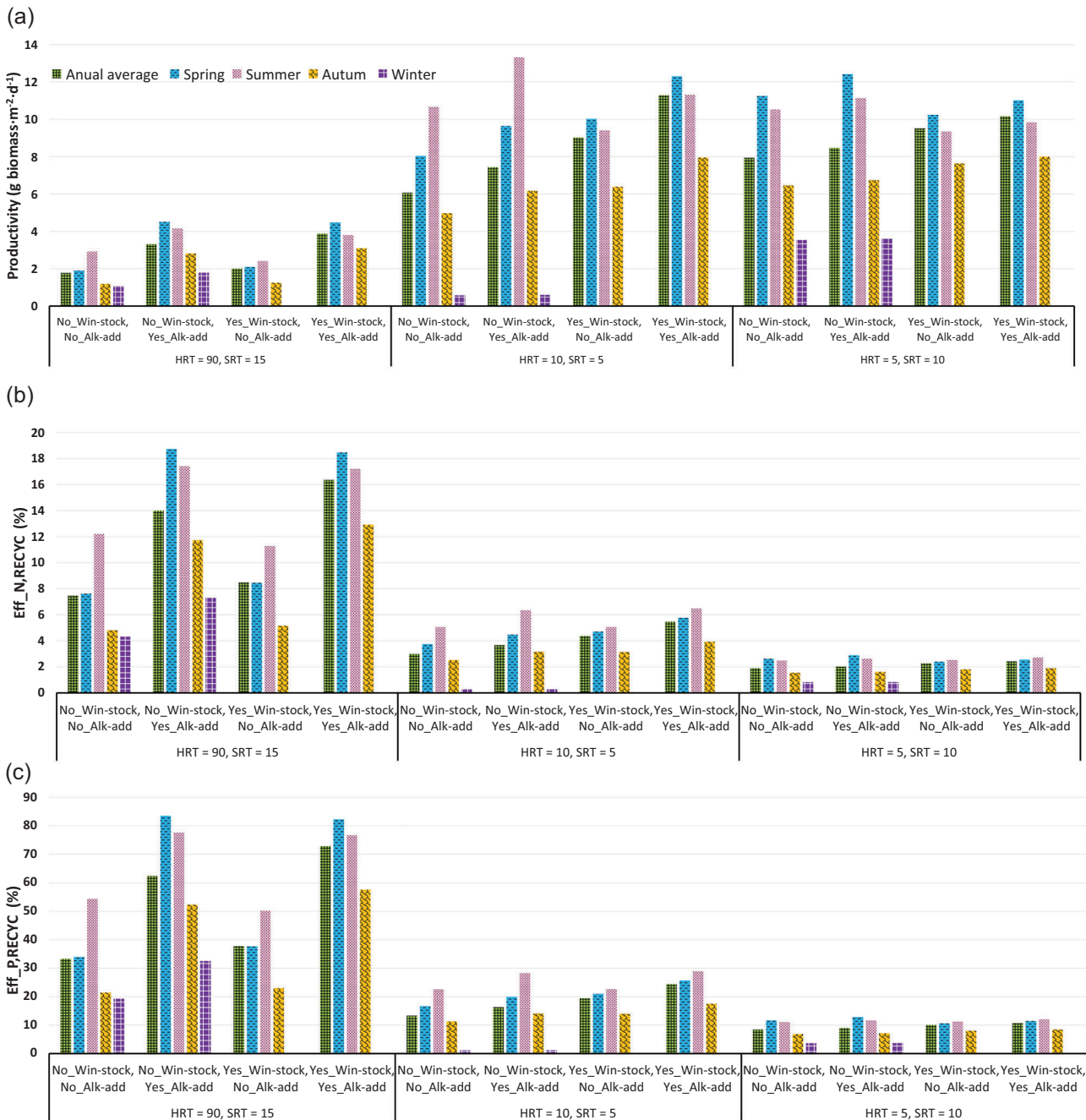


FIGURE 3 Seasonal and annual average variation of the 12 scenarios of microalgae biomass productivity (a) and removal efficiency for nitrogen (b) and phosphorous (c). Note: Underlying data are available in Table 6 of Supporting Information S2. HRT, hydraulic retention time; SRT, solid retention time.

influent N load have been reported for a HRT of 7.5 days by Plouviez, Chambonnière et al. (2019). Thus, N₂O emissions in this case are low, and the addition of soda has only a marginal effect.

Contrasting with the patterns obtained on algal productivity, N and P removal efficiency (Figure 3b,c) is higher for the scenarios (HRT90, SRT15), reaching maximum values around 20% for N and higher than 80% for P (both reached in summer). In autumn and winter, the N and P removal rates were generally below 13% and 57.6%, respectively, due to sub-optimal growth conditions for microalgae and bacteria. The patterns between N (Figure 4b) and P (Figure 4c) removal efficiency are similar, even if the range of variations is totally different (underlying data for Figure 4 are available in Table 7 of Supporting Information S2). The scenarios where HRT is lower than SRT lead to dramatically low removal efficiencies, down to 2.7% for N and 12.8% for P.

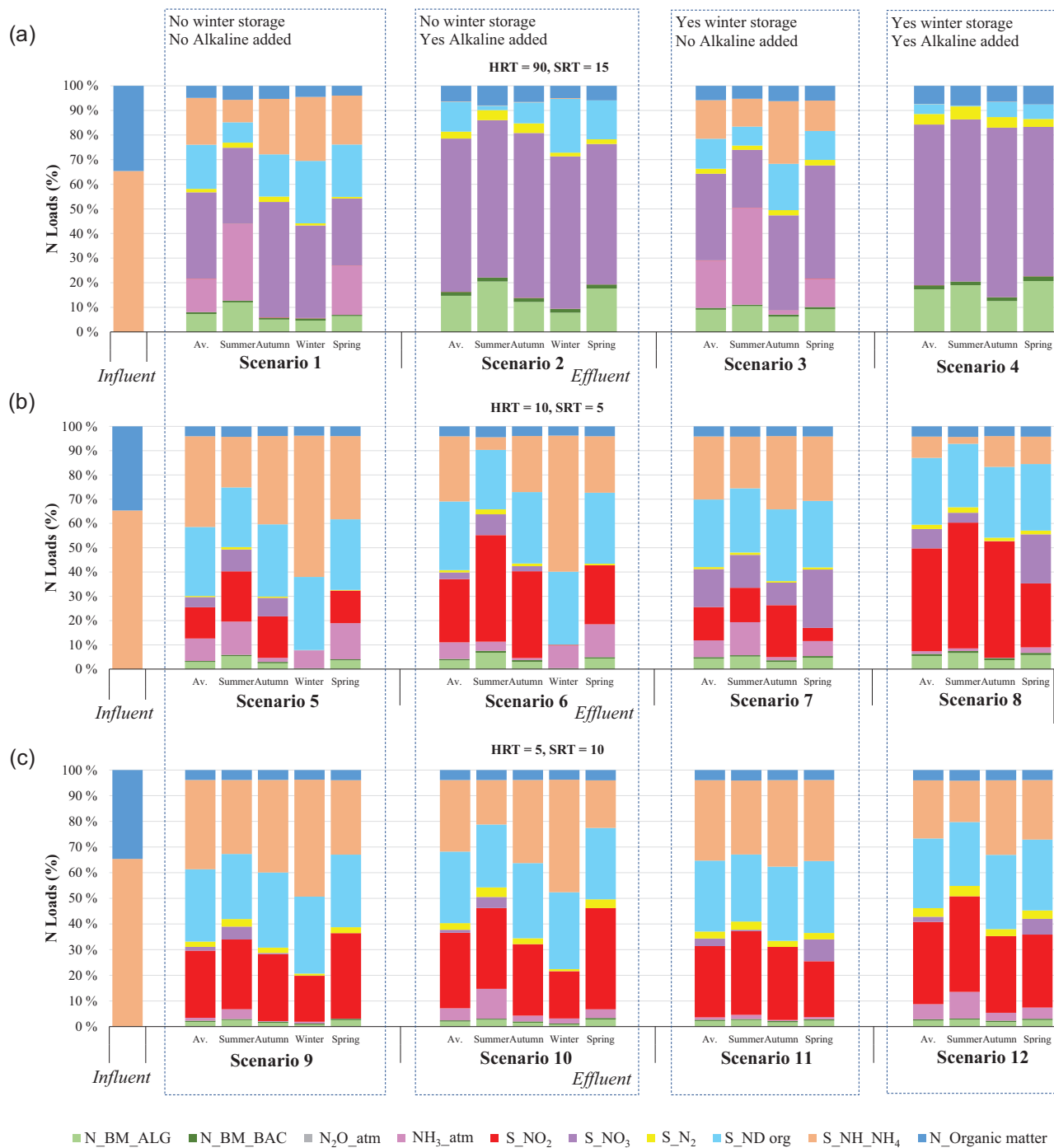
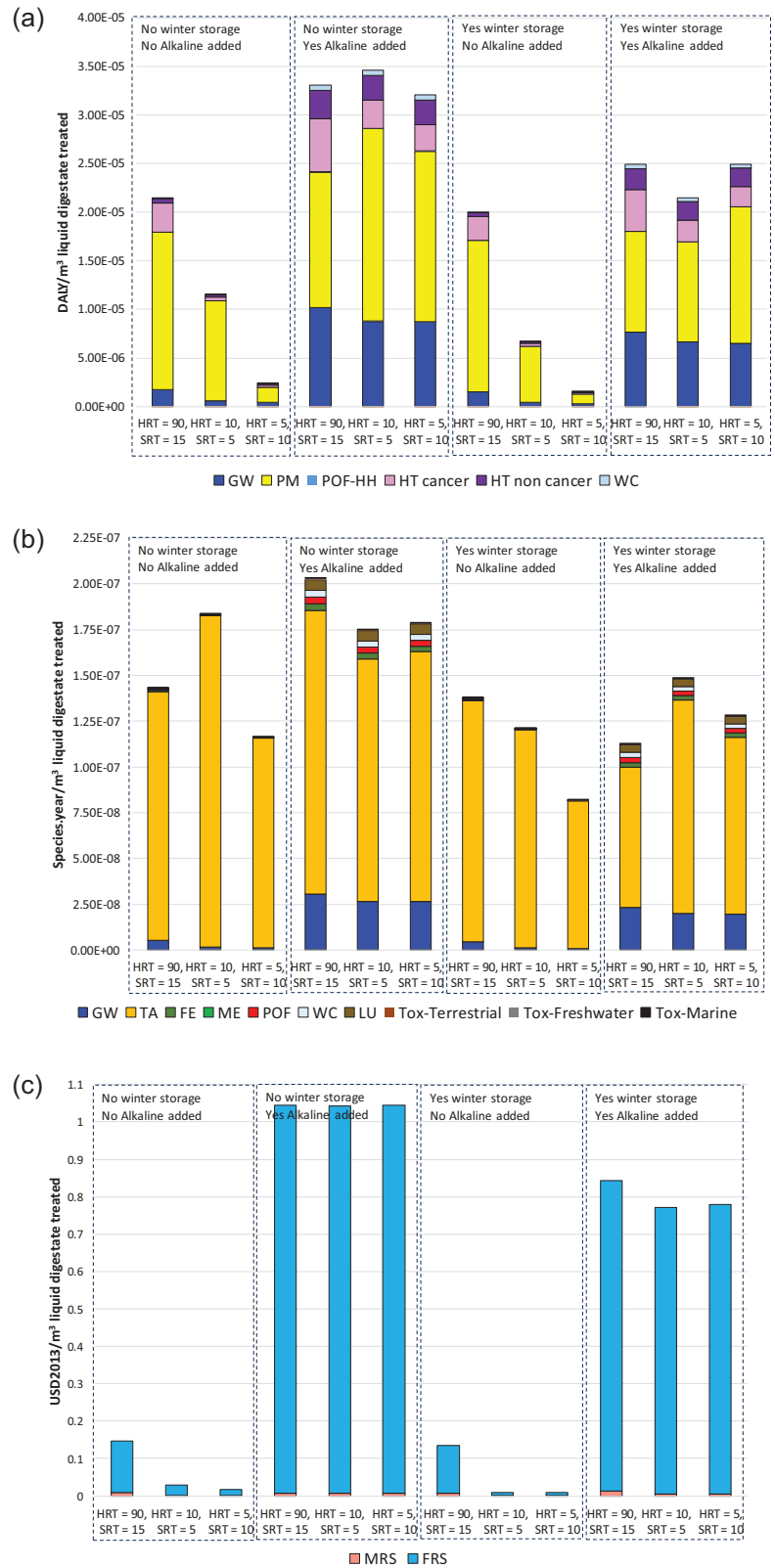


FIGURE 4 Fractionation of the influent and the effluent nitrogen loads for different seasonal (summer, autumn, winter, and spring), alkalinity, and winter storage conditions. Note: Underlying data are available in Table 7 of Supporting Information S2. HRT, hydraulic retention time; SRT, solid retention time.

Alkalinity appears to play a direct role in N and P removal. Adding alkalinity increases the microbial uptake of N and P, in line with other studies (Chan et al., 2014; Vadlamani et al., 2017). Alkalinity conditions also lead to P precipitation and conversion of ammonia in the form of NO_x , that is, nitrate and nitrite, also contributing significantly to overall N and P removal (Chan et al., 2014).

Nitrogen and phosphorus compounds' dynamics are complex since they are affected by all the processes occurring in the reactor, which are highly season-dependent. The fractionations of the influent and effluent of N are shown in Figure 4. The largest fractions of N forms in the effluent are nitrite and nitrate. NO_3^- for the scenarios (HRT90, SRT15) (Figure 4a) and NO_2^- for the scenarios (HRT10, SRT5) and (HRT5, SRT10), as shown in Figures 5b and 5c, respectively. Nitrite and nitrate fractions exceed the fraction of N incorporated into the algal biomass (defined as $\text{N}_{\text{BM_ALG}}$). The

FIGURE 5 Characterization (per functional unit [FU]) of the 12 scenarios, considering hydrothermal liquefaction (HTL) as the conversion option for biomass to energy (average annual biomass productivity considered) at the endpoint level according to ReCiPe (2016) Midpoint (H) v1.03 method. Underlying data are available in Table 9 of Supporting Information S2. HRT, hydraulic retention time; SRT, solid retention time.



largest fraction of N_{BM_ALG} occurs in the scenario with an HRT of 90 days, reaching values of 20% during warm seasons and down to 4.6% during cold seasons, while the minimal values are obtained in the scenarios with an HRT of 5 days (lower than 3%). Temperature plays a direct role in the solubility of dissolved gases and, indirectly through biological rates (Casagli et al., 2021). For example, microalgae and nitrifying activities in autumn and winter slow down so that the biological contribution to ammonium removal is reduced, thus decreasing NO_x concentrations and increasing ammonium concentrations.

The scenarios with alkalinity addition were adequate for algae and nitrifiers, increasing the fraction of $N_{BM,ALG}$ and decreasing the N_2 emissions, respectively. However, increasing alkalinity increased the NH_3 at conditions of HRT of 5 days. This contrasts for HRT of 10 and 90 days where the NH_3 emissions are decreased to negligible values for the scenarios (HRT90, SRT15), and where the N is released as NO_x .

3.2 | Endpoint categories: Identification of the least impacting scenario

The input–output inventories of energetic and chemical demands, as well as the machinery required in each subsystem, are listed in Tables 8a and 8b of Supporting Information S2 for the 36 scenarios evaluated. The endpoint life cycle environmental impacts for treating 1 m³ liquid digestate are shown in Figure 5 (underlying data for Figure 5 are available in Table 9 of Supporting Information S2). It describes the endpoint categories for the twelve scenarios considering HTL as the conversion option for biomass to energy, that is, subsystem 4. HTL conversion technology appears to be the option with the lowest environmental impact and is identified as the most favorable option to be carried out. The values per midpoint impact category contributing to each endpoint and scenario (HTL, WLE, and combustion) are detailed in Table 9 of Supporting Information S2. In terms of damage to human health (Figure 5a), the main categories contributing are GW, PM, and HT (cancer and non-cancer). Besides, the main categories affecting the damage to ecosystems (Figure 5b) are TA followed by GW, while for damage to resource availability (Figure 5c), FRS is almost the only contributing category. No substantial difference is observed between the biomass conversion options (HTL, combustion, and WLE). This is explained by the low contribution of subsystem-4 to the total impact (overwhelmed by other subsystems, see contribution by subsystem in Table 10 of Supporting Information S2), which is the only difference between the three down processing scenarios. Overall, the lowest impacts for the three endpoint categories are obtained when HRT is low, highlighting both the influence of algal productivity and the subsequent reduction in the number of required ponds regarding environmental loads.

The dose of added soda in the cultivation system has an increased impact effect on the endpoint categories, especially for damage to human health and resource availability. This results both from the burden associated with the production of NaOH for human health and resource depletion, together with the increase in the emissions of inorganic nitrogen (gaseous NH_3 and dissolved NO_3). Unexpectedly, the winter storage of the liquid digestate decreased the human health, ecosystems, and resource availability impacts, by avoiding the cold periods at very low microalgae productivity. In this case, and without soda addition, the scenario with the lowest environmental load is scenario 11 (HRT5, SRT10), which reports 20.4% and 20.1% lower impacts on damage to human health and ecosystems, respectively, and slightly higher (6.2%) in resources, in comparison to the second-best option (HRT10, SRT5), in scenario 7. Midpoint categories for selection of the least impacting scenario are analyzed in Section 11 of Supporting Information S1.

3.3 | Environmental impacts by category and input contribution

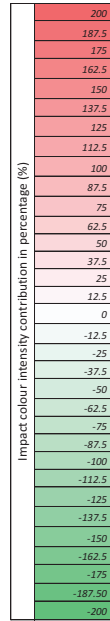
Analyzing the hotspots in the less impacting scenario 11 (see Table 2) provides a better insight into the most impacting steps. Here, based on the endpoint analysis, we focus on the most contributing categories: GW, TA, FE, ME, HT (cancer and non-cancer), PM, and FRS. It should be noted that NaOH is the main contributor to most of the environmental burdens for the scenarios with alkalization, due both to NaOH production, and also to the increase in NH_3 stripping (affecting TA and PM) and dissolved NO_3 (affecting ME). Subsystem 3 has a strong contribution to all the indicators, reporting both positive and negative (impacts avoided) values. The diesel consumption (and associated emissions) due to the tractor spreading the N-fertilizer (from subsystem 3), as well as NH_3 and NO_2 emissions from land application of N-fertilizers (from subsystem 3), are the main contributors. Note that this impact is masked in most of the other scenarios where NaOH is added due to the strong increase in the related impact. This scenario reaches 0.30 kg CO_2 eq·m³ for GW and 0.37 kg SO_2 eq·m³ of treated liquid digestate for TA. N volatilization after N-fertilizer on land application, mainly N_2O , contributes significantly to GW and A, followed by the emissions associated with diesel consumption by the spreading tractor. A similar pattern can be found for the categories FE, HT (cancer and non-cancer), FRS, and PM, which is almost exclusively due to the spreading tractor used for fertilizer application in subsystem 3, because of the diesel and combustion emissions associated with the spreading process. Contrasting with the rest of the impact categories, the contributions to ME are almost exclusively due to the avoided N-mineral fertilizer and its associated emissions. The avoided emissions affecting ME are mainly related to NO_3^- reaching surface water.

3.4 | Which technological progress could further decrease the environmental footprint?

This study focused on the most widespread microalgae production systems from wastewater. However, emerging technologies could reveal more efficient systems, with less impact, such as rotating algal biofilms where the algae grow attached to a rotating surface (Christenson & Sims, 2012; Gross et al., 2013). The energy demand of these systems is reduced by moving only the biomass, avoiding mixing large amounts of water, and the separation system is naturally facilitated by straightforward harvesting of the biomass by simple scraping. This process demonstrated better

TABLE 2 Contributions of the main inputs to the different impact categories for scenario 11. ReCiPe (2016) Midpoint (H) v1.03 method.

			CC	TA	FE	ME	HT non cancer	HT cancer	PM	FRS	
Culture - S1	INPUTS										
	Chemicals	Sodium hydroxide (NaOH)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	Infrastructure	PVC liner facility	3.10	0.05	0.25	0.00	0.02	21.55	1.18	4.25	
		Pond (concrete)	0.10	0.00	0.18	0.00	0.10	0.09	0.04	0.06	
	Machinery	Pump digestate (steel)	0.44	0.01	3.05	0.00	2.12	4.71	0.37	0.30	
		Blower (steel)	0.44	0.01	3.05	0.00	2.12	4.71	0.37	0.30	
		Paddlewheel (steel)	0.07	0.00	0.46	0.00	0.32	0.71	0.06	0.05	
	Electricity consumption	Pump digestate	0.18	0.00	0.49	0.00	0.25	0.17	0.11	0.16	
		Blower CO ₂	0.03	0.00	0.07	0.00	0.04	0.03	0.02	0.02	
		Motor paddlewheel	0.05	0.00	0.14	0.00	0.07	0.05	0.03	0.04	
	OUTPUTS										
	Infrastructure dismantling	PVC to treatment	1.08	0.00	0.34	-0.01	0.59	0.44	0.09	0.14	
		Concret to treatment	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.02	
		Steel to treatment	0.03	0.00	0.01	0.00	0.01	0.01	0.03	0.04	
	Environment emissions	CO ₂ atm_echange	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
		N ₂ O_atm (emission)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
		NH ₃ _atm	0.00	4.88	0.00	0.00	0.00	0.00	48.95	0.00	
S2 - Biomass concentration	INPUTS										
	Electricity	Pump settling IN	1.06	0.02	2.97	-0.03	0.46	1.02	0.68	0.95	
		Pump settling OUT	0.02	0.00	0.05	0.00	0.01	0.02	0.01	0.02	
		Membranes	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	
		Centrifuge	0.01	0.00	0.02	0.00	0.00	0.01	0.00	0.01	
		Pump recirculating	1.06	0.02	2.97	-0.03	0.46	1.02	0.68	0.95	
	Machinery	Membranes (steel)	0.04	0.00	0.30	0.00	0.07	0.47	0.04	0.03	
		Centrifuge (steel)	2.22	0.03	15.24	-0.01	3.59	23.54	1.85	1.51	
		Settling pumps (steel)	0.38	0.01	2.62	0.00	0.62	4.05	0.32	0.26	
		Pump recirculating (steel)	0.38	0.01	2.62	0.00	0.62	4.05	0.32	0.26	
		Settling (concrete)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	OUTPUTS										
	Infrastructure dismantling	Steel to treatment	0.10	0.00	0.05	0.00	0.02	0.03	0.11	0.12	
		Concrete to treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	S3 - Water treatment	INPUTS									
		Electricity	Ultrafiltration + Reverse Osmosis	0.26	0.00	0.56	0.00	0.16	0.12	0.19	0.51
		Chemicals	Ultrafiltration + Reverse Osmosis	0.37	0.01	2.55	0.00	1.47	0.21	1.66	2.30
Transport		Truck km	19.88	0.04	9.77	0.00	6.51	2.96	12.08	52.80	
Land application		Retentate + Concentrate	84.99	0.26	137.71	0.02	120.17	40.94	85.45	168.94	
OUTPUTS											
N - Emissions		Land application	181.59	94.95	0.00	0.00	0.00	0.00	0.00	0.00	
Avoided products	N - Fertilizer	-197.92	-0.30	-85.48	-100.11	-39.81	-10.89	-54.64	-134.05		



environmental performances than ORPs through several LCA studies (Morales et al., 2020; Penaranda et al., 2023). Other energetic valorization approaches of microalgae are likely to demonstrate decisive advantages, such as reinjecting the biomass in the digester to enhance the biogas production (Sialve et al., 2009), most probably by involving additional pretreatment steps (Zabed et al., 2020). These approaches can also be coupled with solar drying strategies to further concentrate the algal biomass or the fertilizer (Castro et al., 2020) and reduce the amount of water to be transported. Also, when considering the footprint due to transportation, an irrigation network in the perimeter of the plant could supply water and nutrients to cultures and favor a local circular economy. These scenarios show that the microalgae pathway is still young and technologically immature, and breakthroughs are expected to further improve its efficiency. Analyzing the environmental benefit of these new options is therefore crucial but at the cost of a combinatorial explosion of the scenarios to be studied in the LCA.

3.5 | The determinant role of fertilizer transportation

The macronutrients in the liquid digestate can replace the use of strongly impacting mineral fertilizers and thus have clear environmental benefits (Haraldsen et al., 2011; Sigurnjak et al., 2017). Importantly, the concentration of N in the liquid digestate (0.66 kgN·m⁻³) is much lower than in the liquid N-fertilizer obtained in subsystem 3 through ultrafiltration (9.4 kgN·m⁻³ for scenario 11). The direct use of liquid digestate means transporting much more water. Indeed, 60.67 tonnes of untreated liquid digestate must be transported while 15 tonnes of liquid N-fertilizer must be managed as the output of scenario 11, with a more concentrated and purified product of higher value. The transport of these two large liquid volumes plays a strong role in the impact assessment. Figure 5 (Supporting Information S1) shows simulations of different transport distances (from 1 to 10 km) affecting the categories of GW, TA, FE, ME, HT, PM, and FRS, for the baseline scenario (direct liquid digestate application) and the optimal scenario 11. For most of the evaluated categories, the baseline scenario represents a higher environmental load, except ME, HT cancer, and PM. The benefits are higher for ME with the liquid digestate, since more N-emissions are avoided, that is, due to a higher mass of N. Indeed, this nitrogen is lost through denitrification or by microalgae and bacteria consumption. Below 9 and 4 km, the impact of the liquid digestate stays comparable with liquid N-fertilizer in HT cancer and PM, respectively. Beyond the issue of liquid transportation, the land area required for spreading the liquid digestate or the N-fertilizer differs. Direct land application requires 1.2 ha of land per day, while around 0.9 ha per day is necessary to spread the liquid N-

fertilizer. The liquid N-fertilizer obtained from the microalgae exhibits improved inherent quality after ultrafiltration. However, its effect on crop cultivation efficiency, compared to liquid digestate, should be further characterized, but this is beyond the scope of this study.

The N-liquid fertilizer is also likely to be exported to other markets due to its higher economic value. Additionally, storing digestate during winter is a more practical approach, as it allows the production of N-fertilizer only when it can be effectively utilized.

4 | CONCLUSIONS

This study first outlined that clearly defining the main goal of the process is crucial, especially when it can be used for two conflicting objectives: for liquid digestate treatment (removal N and P), or to produce microalgal biomass, bioenergy, or fertilizer. The scenarios at high HRT resulted in 19% of N and 80% of P removal efficiency, but this was associated with low microalgae productivity (up to 3.9 g/m²/day) and was eventually up to 18 times more impacting than scenarios at low HRT. The best design and operational strategies to reach the lowest environmental impact (at endpoint and midpoint levels), associated with higher productivity, was for HRT of 5 days and SRT of 10 days, with a winter storage and without alkalinity addition. In this scenario, microalgae productivity reaches up to 10.15 g/m²/day (in summer) but the inorganic pollutants' (N and P) removal rates decreased down to 2.7% for N and 12.8% for P. Therefore, this strategy makes sense only for bioenergy or biomass production. Unexpectedly, increasing alkalinity to avoid N₂O production results in side effects, enhancing by up to 48 times the impact in some categories related to toxicity and water consumption. The option of storing the digestate during winter turned out to drastically reduce the environmental burdens by up to twofold. Considering a module with culture water recycling and treatment allowed to compensate for the water demand in the system but negatively impacted some other categories. Advanced post-treatment for recycling water is a good option in comparison to spreading untreated liquid digestate, depending on the digestate transportation distance. The three families of scenarios with various energetic valorization of the biomass do not show significant differences so economy should be the decisional criterion.

Liquid N-fertilizer from microalgae has a higher quality (higher N content), is more land-efficient, and has a lower environmental impact than directly spreading liquid digestate on land. Microalgae-based processes can play a significant role in liquid digestate valorization, but this ex ante LCA study highlights the complexity of the problem, and how the drawbacks of an apparently attractive option can immediately jeopardize its benefit.

Climate is crucial to the analysis, and different conclusions could emerge under varying climates. Nordio et al. (2025) show that algae–bacteria dynamics can be predicted accurately in warmer climates, making this methodology applicable to any location. A warmer climate would enhance process efficiency and reduce environmental impact.

This ex ante LCA analysis shows that mathematical modeling is necessary to quantify and solve the numerous trade-offs and guide scaling-up optimization through the complexity of the multiple scenarios assessed along a multicriterial analysis.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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