Advanced near-zero waste treatment of food-processing wastewater with water, carbon, and nutrient recovery

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**Highlights (3-5, max 85 chara)**

* AnMBR combined with outdoor microalgae cultivation and HTC was studied.
* A near zero-waste treatment of food process wastewater scheme is demonstrated
* Carbon was recovered as biogas and hydrochar, nitrogen and phosphate as microalgae biomass
* Biomass productivity and nutrients uptakes changed seasonally and with N to P ratio
* High effluent quality for reuse was attained after 2d in summer and 5 in winter

# Graphical abstract (5\*13 cm)



**Abstract (100-150 words)**

A near-zero waste food-process wastewater treatment was developed and studied. The wastewater was treated by anaerobic membrane bioreactor (AnMBR), polished by outdoor photobioreactor for microalgae cultivation (with three species were studied), and excess sludge was treated by hydrothermal carbonization. The study was conducted under arid climate conditions for a year (four seasons). The AnMBR reduced the total organic carbon by 97% that was partially recovered as biogas and hydrochar. Microalgae biomass productivity ranged from 0.25-0.8 g/L-day. Nutrients uptake (25-55 mg∙L-1-day TN and 1-5 mg∙L-1-day TP), and mass balance analysis demonstrated high efficiency of the process to recover C, N, and P. The microalgae strains performed similarly with minor seasonal effects. Effluent standards for irrigation were attained within 2 and 5 days in summer and winter, respectively. Overall, a near-zero waste discharge producing high-quality effluent, nutrients recovery into microalgae biomass, and energy production as biogas and hydrochar is demonstrated.

**Keywords (max 5)**

Anaerobic membrane bioreactor, food industry wastewater, microalgae cultivation, nutrient recovery, hydrothermal carbonization.

# Introduction (max. 3 pages)

Wastewater is becoming an important resource for water, energy, and nutrients (Batstone et al., 2015; Shannon et al., 2008; Tee et al., 2016). However, the common current wastewater treatment technologies (WWT), such as activated sludge, are energy-intensive and underuse or neglect stored energy and recovery of valuable nutrients, namely, phosphorous (P) and nitrogen (N) (Hunter et al., 2019; N. Li et al., 2020). Moreover, these technologies often generate substantial quantities of greenhouse gases (GHG) and large volumes of unwanted residual sludge (Maktabifard et al., 2020). The use of anaerobic membrane bioreactors (AnMBRs) presents a promising low-carbon-footprint alternative to common WWTs for organic matter decomposition and energy recovery (Maaz et al., 2019; Neoh et al., 2016; Robles et al., 2020b). In particular, AnMBR is highly suitable for high strength industrial wastewater, such as food processing wastewater, where the total organic carbon (TOC) concentration is high (often >0.5 g/L) and mostly biodegradable (Dereli et al., 2012; Y. Li et al., 2020; Tee et al., 2016).

The application of AnMBRs for industrial wastewater treatment and lately for urban wastewater with a positive energy balance has been reported before on a lab-scale and pilot-scale (Galib et al., 2016; Robles et al., 2020b) while full-scale systems are expected to be realized in the coming years (Cashman et al., 2018; Pretel et al., 2016; Robles et al., 2020b; Smith et al., 2014). Nevertheless, as most of the nutrients (i.e. nitrogen and phosphorus) remain in the AnMBR effluent, a post-treatment step for nutrient removal is required for subsequent discharge or reuse. The very low nutrients removal in the AnMBR, however, can be regarded as an advantage of the AnMBR technology as the nutrients can be easily recovered from the high-quality effluent (Robles et al., 2020a; Song et al., 2018). Nutrients recovery can also increase the sustainability and economics of AnMBR (Robles et al., 2020a; Smith et al., 2012).

A widely publicized sustainable wastewater treatment process specifically for reducing nutrients is by microalgae cultivation (Nagarajan et al., 2020). Valorization of the microalgae biomass following cultivation is an added advantage of this approach (Khoo et al., 2019; Koutra et al., 2018). In particular, the nutrient-rich effluent of anaerobic treatment of food-process wastewater and the CO2 that is produced during this process in the biogas, provide ideal substrates for microalgae cultivation (Franco-Morgado et al., 2018; Yan et al., 2016).

The application of using microalgae as a polishing step to reduce nutrients, carbon, metals and other toxic compounds of effluent from various sources have been vastly investigated before and reached large-scale, mostly using raceways configuration, (Baral et al., 2020; K. Li et al., 2019; Robles et al., 2020a). However, the application of raceways for water recovery following cultivation under desert climate can be challenging due to high water evaporation, especially when the effluent contains high nutrients load (Handler et al., 2012; Nwoba et al., 2016). Cultivation in close or hybrid reactors, such as photobioreactor (PBR), can limit water evaporation and also improve the overall process (Cai et al., 2013).

The combination of AnMBR with microalgae for effluent post-treatment in PBR was also already successfully demonstrated by several authors (Pachés et al., 2018; Pretel et al., 2016; Vu et al., 2020). In recent studies, (González-Camejo et al., 2019a) highlighted the importance of temperature and irradiance as well as the light-path and the non-controlled variables (such as P, NH4+, etc.) on nutrient removal rates and process efficiency during long-term outdoor polishing experiments of AnMBR effluent. The importance of these parameters on the process efficiency was further established in a 3 years operation of PBR outdoor microalgae cultivation in AnMBR effluent (González-Camejo et al., 2020). However, in many of these studies, even though the influent was domestic wastewater and thus contained relatively low TN concentrations (30-80 mg∙L-1), long HRTs (typically 4-6 days) in the PBR were needed (due to low TN uptake) to meet water quality standards for unlimited reuse. The HRTs are expected to be much longer for effluent containing high nutrients loading as food industry wastewater (Cai et al., 2013). The long HRTs will impose high cooling and energy costs as well as high water losses of the treated due to water evaporation. Furthermore, many of these studies were conducted under controlled temperature and irradiation. As discussed above, the seasonal variability of microalgal productivity can pose a great challenge in operating such microalgae-based remediation processes. Therefore, it is suggested that these processes will be tested under realistic setup outdoors during all seasonal climate variations and under natural conditions (i.e., without temperature and light control) (Almomani et al., 2019; González-camejo et al., 2017; Hulatt and Thomas, 2011).

The goal of this research was to develop, investigate and analyze a near-zero waste discharge food processing wastewater treatment scheme comprises AnMBR with outdoor PBR microalgae cultivation and hydrothermal carbonization under realistic arid-desert climate conditions for the production of high-quality effluent, recovery of nutrients, carbon, and energy.

# Materials and methods

## *Lab-scale submerged anaerobic membrane bioreactor*

A 15 L high-throughput lab-scale submerged AnMBR (schematically described in Fig. 1) equipped with six membranes (PES 150 kDa, Microdyn-Nadir, Germany) was built and operated (AnMBR operational conditions are listed in Table S1) for over two years (Grossman et al., 2019). The reactor was fed with real industrial wastewater taken from a potato and corn snack factory (Strauss – Frito-Lay, Sha’ar Hanegev, Israel). Wastewater was tested every three days as described below, in section 2.4.

The filtration was conducted under sub-critical flux with 9 min filtration and 1 min backwash. The critical flux was measured as described by (Diez et al., 2014). Chemical cleaning of the membrane was applied every 3-4 months by soaking the membranes in 0.5% NaOCl for 30 minutes. Biogas composition and production were measured daily using a biogas analyzer (Biogas 5000, Geotech, UK).



**Fig. 1.** Schematic illustration of anaerobic membrane bioreactor (AnMBR), hydrothermal carbonization (HTC), and an outdoor photobioreactor (PBR) with thermoregulation system for combined treatment of industrial wastewater. PBR was operated as a batch reactor in a semi-continuos mode with a column for each microalgae strain. AnMBR wasted sludge was treated by HTC.

## *Microalgae cultivation*

Three microalgae strains were tested:two local thermotolerant strains isolated in Sde Boker (Belete et al., 2019) - *Coelastrella* sp.(similar to *Coelastrella saipanensis)* and *Chlorella* sp., and *Scenedesmus* sp. isolated and tested previously in Germany for wastewater applications (Han et al., 2019). Each microalga was cultivated using an outdoor photobioreactor cylindrical column (PBR) with 2.5L effective volume and horizontally illuminated area of 55 cm2 (with a total of 110 cm2 transparent area) located in the Sde Boker campus of Ben-Gurion University (Israel) under a desert climate. The PBR columns were thermoregulated in a water bath with cooling water from a below-ground reservoir that was circulated to and from the water bath (Fig. 1). Water evaporation losses from the column were measured daily.

Before the outdoor experiments started, the microalgae species were adapted and tested using AnMBR effluent (supplementation with Fe-EDTA and microelements stock solution of the mBG11 medium) in indoor conditions in 150 ml Erlenmeyer flasks as described previously (Belete et al., 2019).Then, the microalgae were transferred to the columns for an outdoor adaptation for one week. The microalgae outdoors cultivation was performed all-year-round. The experiments and analysis were conducted in four seasons (May-Spring, July-Summer, November-Fall, and January-Winter) and measuring three-four distinct growth cycles for each season. The PBR operated as a batch reactor by introducing fresh effluent before every growth cycle and was bubbled with 1 L/min air/CO2 (98%/2%) mixture. The cultures were refreshed every 4 - 7 days (a growth cycle) by a five times dilution factor (0.5 L culture with 2 L fresh AnMBR effluent).

* 1. *Hydrochar production*

Hydrothermal carbonization (HTC) of the AnMBR sludge was carried out in a 50-mL stainless-steel tubular reactors by introducing in a dry AnMBR sludge: water ratio of 1:3. Reactors with one cylinder equipped with a temperature probe were heated at 210 °C for 4h by immersion in Paratherm HR heat transfer fluid (Mau et al., 2019). After the desired temperature and time, reactors were placed in an ice bath to rapidly quench the process. Following this, the slurry was centrifuged and then wet-hydrochars were dried at 105 °C. The HTC ultimate analysis (carbon, hydrogen, nitrogen, and sulfur content) was measured by a CHNS-O analyzer (Flash 2000 Elemental Analyzer, Thermo Fisher Scientific Inc., UK). The remaining component after the subtraction of ash, C, H, N, and S was considered as oxygen content (ASTM-D3176, 2015). Ash content was determined by heating samples at 450°C for 6 h in a muffle furnace (ASTM, 2015).

* 1. *Water and biomass characterization*

At every growth cycle, the microalgae growth (measured based on dry weight), total nitrogen (TN), total ammonia nitrogen (TAN), and total phosphorus (TP) concentrations in the growing media were determined daily. Sampling was done by taking 50 mL aliquots at noon from each column. Microalgae biomass dry weight was measured by filtering of 5 mL of culture through weighed GF/C filters in duplicate and determining the microalgae dry weight as described by Belete et al. (2019). The remaining 40 ml of culture were centrifuged at 3000 rpm for 10 min and the supernatants were stored for nutrient and water analyses. The microalgae pellets were washed in DDW and stored at -80°C for determining phosphate content.

The biomass productivity (P) and TP, TAN and TN uptakes (V) were measured by:

For the case of biomass, where c is the initial (i) and final (f) of the biomass, N or P concentrations (mg∙L-1) during a growth cycle of cycle time tc of semi-continuous operation. The biomass productivity and the TN, TP, and TAN were measured for each growth cycle until the TN concentration reached the Israeli TN standard for unlimited irrigation (TN < 25 mg∙L-1).

The food industry wastewater, AnMBR effluents, and microalgal treated supernatants (following harvesting) were characterized: pH, and electrical conductivity (EC) by CyberScan Con11 and pH11 (Eutech Instruments Ptv. Ltd., Singapore), respectively; TN, TOC, and DOC by a TOC analyzer (Multi N/C, Analytik-Jena, Germany), TSS by the through the gravimetric method, and macro/micro-nutrients using an inductively coupled plasma (ICP) analyzer. The analyses were done by standard methods and as described in our previous study (APHA, 2005; Belete et al., 2019). The P-content of microalgae biomass was determined following the digestion of the microalgae by microwave (ETHOS UP, Milestone, Italy). Dry biomass (up to 50 mg) was dispersed in 8 mL 65% HNO3 and 2 mL 30% H2O2 and placed in a PTFE-TFM-Teflon 100 mL microwave vessel. The digestion was done for 30 min at a 210 °C maximum temperature, and the microalgae were fully decomposed into the solution. The liquid was filtrated and TP concentration was measured by ICP-OES (Spectra, Germany).

## *Statistical analysis*

## The differences in the biomass productivity and nutrients uptakes between the three stains in each season, and between four seasons for each strain were analyzed by a two-way ANOVA followed by post-hoc Tukey HSD statistical analysis using Rstudio 1.1.463 for R 3.5.1 software for windows (The R Foundation for Statistical Computing).

# Results and discussion

# *Industrial wastewater treatment by AnMBR*

Raw wastewater and AnMBR-treated effluent characteristics are presented in Table 1. The TSS and the TOC removal were over 99% and 97% respectively throughout the experiment. It also shows that a constant AnMBR effluent quality was obtained despite varying TOC concentrations in the influent. In addition, the high TOC removal indicates the high biodegradability of the organic matter in the food processing wastewater. The TN and TP concentrations in the influent and the AnMBR effluent were almost similar and a high fraction of the TN was converted from organic nitrogen in the influent to ammonium in the AnMBR effluent (Table 1). The increase in the effluent conductivity was due to NaOH addition that was needed to keep a constant pH value. The increase in the EC can be significantly limited by replacing NaOH with CaHCO3. It is noted that the EC of most food-process wastewater makes the effluent applicable for irrigation of tolerance crops (such as dates or tomato) or hydroponic. Alternatively, the effluent can simply be diluted to lower the salinity for unrestricted irrigation (EC<1.4 S/cm in Israel). The macro- and microelements concentrations, besides sodium (due to the addition of NaOH), did not change (Table S2).

Table 1. Water quality and process performance in the anaerobic membrane bioreactor (AnMBR).

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Influent (feed) | Effluent (permeate) | Removal (%) |
| TSS (mg∙L-1) | 2093±199 | ˂10 | >99.9% |
| TOC (mg∙L-1) | 1520±715 | 32.3±6.5 | 97.9±% |
| DOC (mg∙L-1) | 916.2±95.1 | 32.3±6.5 | 96.5% |
| TN (mg∙L-1) | 165±81 | 153.7±15.8 | 6.7% |
| TP (mg∙L-1) | 9.9±4.8 | 9.2±4.5 | 7.1% |
| pH | 7.0±0.2 | 7.3±0.2 | - |
| EC (mS/cm) | 2.2±0.3 | 3.0±0.4 | - |

One of the main advantages of AnMBR is the recovery of the organic carbon in the form of biogas. The average biogas production during the wastewater treatment was 8.1 L/day with an average composition of 77±6% CH4, (i.e., an average methane yield of 0.28 L CH4 /g COD removed), 21±4% CO2, and of H2S 780±530 ppm. Furthermore, an average of 0.3 g of excess dry sludge was removed per 1 L of treated wastewater to maintain SRT to HRT ratio of about 30. The SRT: HRT was in the range which is typically found for AnMBR treating industrial wastewater (Han et al., 2018); to obtain a near-zero waste discharge process, the organic carbon in the sludge was recovered in the form of hydrochar, as later discussed.

One of the critical challenges in AnMBR is membrane fouling that causes an increase in the trans-membrane pressure (TMP) of the membranes with filtration time. In this study, the fouling was kept relatively low, as was determined by the stable TMP during the experiments (-15<TMP<-40 mBar), by applying relatively low flux (average flux Jv=4 L/m2h), much lower than the critical flux (≈12 L/m2h), and by implementing biogas sparging and backwashing of the membrane as described in details by (Grossman et al., 2019).

* 1. *Microalgal cultivation, nutrient uptake, and effluent characteristics* 
     1. Biomass growth and productivity

Three microalgae strains, *Coelastrella sp. Chlorella sp. and Scenedesmus sp.* were cultivated outdoors using the AnMBR effluent. The biomass growth and the filtered effluent quality were measured daily. TN, TAN, and TP concentrations in the course of algae cultivation were measured daily.

The microalgae biomass growth of the three microalgae strains and the change in the nutrients in the growth media (TN, TAN, and TP) during fall in three growth cycles Figure 2). The dashed line in Figure 2 represents the number of days to reach both the TP (<5 mg∙L-1 ) and TN (<25 mg∙L-1 ) regulatory standards (Israel) for unlimited irrigation (Inbar, 2007).

The growth periods in summer, winter, and spring are presented in Figs S1-3. As expected the microalgae biomass increased, while TN and TP decreased during a cultivation cycle (see Figure 2 and figures S1-3). The effluent reached the regulatory TN and TP concentrations within 2-5 days depending on the season. In contrast to TN, TP was consumed faster and completely.



**Fig. 2.** The change in the biomass, TN, TAN, and TP concentrations during three cycles in the fall of the three microalgae strains: *Chlorella* (black), *Scenedesmus* (dark grey),and *Coelastrella* (light grey). Vertical grey dash lines represent the day in each cycle where both the TN and TP met the Israeli regulation standards for unlimited irrigation (TN <25 mg∙L-1 ; TP <5 mg∙L-1 ).

The average biomass productivity for each species and at each season (measured based on Figs 2 and S1-3) is presented in Fig.3. The biomass productivity for all three species was generally the highest in the summer compared to the three other seasons (p<0.05), besides *Scenedesmus* between summer and fall (p=0.5). The high productivity in summer was most likely due to favorable climate conditions in terms of temperature, daylight time and radiation (Fig. S4)(Chu et al., 2015)

The similar biomass productivity of *Scenedesmus* between summer and fall suggests that the performance of this species is more sensitive to the summer desert climate compared to the other two species. From Fig. 3 it was also found that interestingly, the biomass productivity of all three species during these periods was not significantly different between spring, summer, and fall although the climate conditions for microalgae growth in spring were on average much better than the conditions in fall and winter (Fig. S4). This generally may be attributed to the high variability of key limiting factors for optimal biomass productivity between these growth periods under realistic uncontrolled outdoor conditions (i.e., irradiation and temperature) and using real effluent (TN, TAN, and TP concentrations and N/P) (K. Li et al., 2019). In particular, in our study, it was found that in spring, the TAN concentrations were much lower than in fall and winter (p<0.01) (see Fig. 2 and S1-3). The low TAN in spring was probably due to the lower conversion of TN to TAN in the AnMBR (Fig. S2). It was also found that the TP concentration during a few cycles in spring (Fig.S2) was very low (TP< 2ppm), which may have influenced the results of this growing season.

In this research, the three species were isolated from two regions having different climate conditions. However, there were no significant differences in the average biomass productivities at a specific season between the three species. The variations in effluent quality and climate conditions that were also recorded between cycles at a specific season can be the reason for the similar biomass productivity. Nevertheless, Fig. 2 and S1-3 suggest that there were species-specific seasonal effects on biomass growth in summer and winter. In summer (Fig. S1) the cold-climate *Scenedesmus* strain during most cycles was less productive than the desert locally isolated *Chlorella* and *Coelastrella* strains, with 25%-30% lower productivity. In winter and fall (Fig. S2-3), the *Chlorella* strain was 15-25% less productive than the two other strains. These differences (and also differences in the nutrients uptake that are discussed below) may be attributed to the adaptation of the microalgae to summer or winter climate, as is often reported by others (Ferro et al., 2018; Y. Li et al., 2019; Xu and Hu, 2013), but further controlled systematic research should be done to establish this hypothesis.

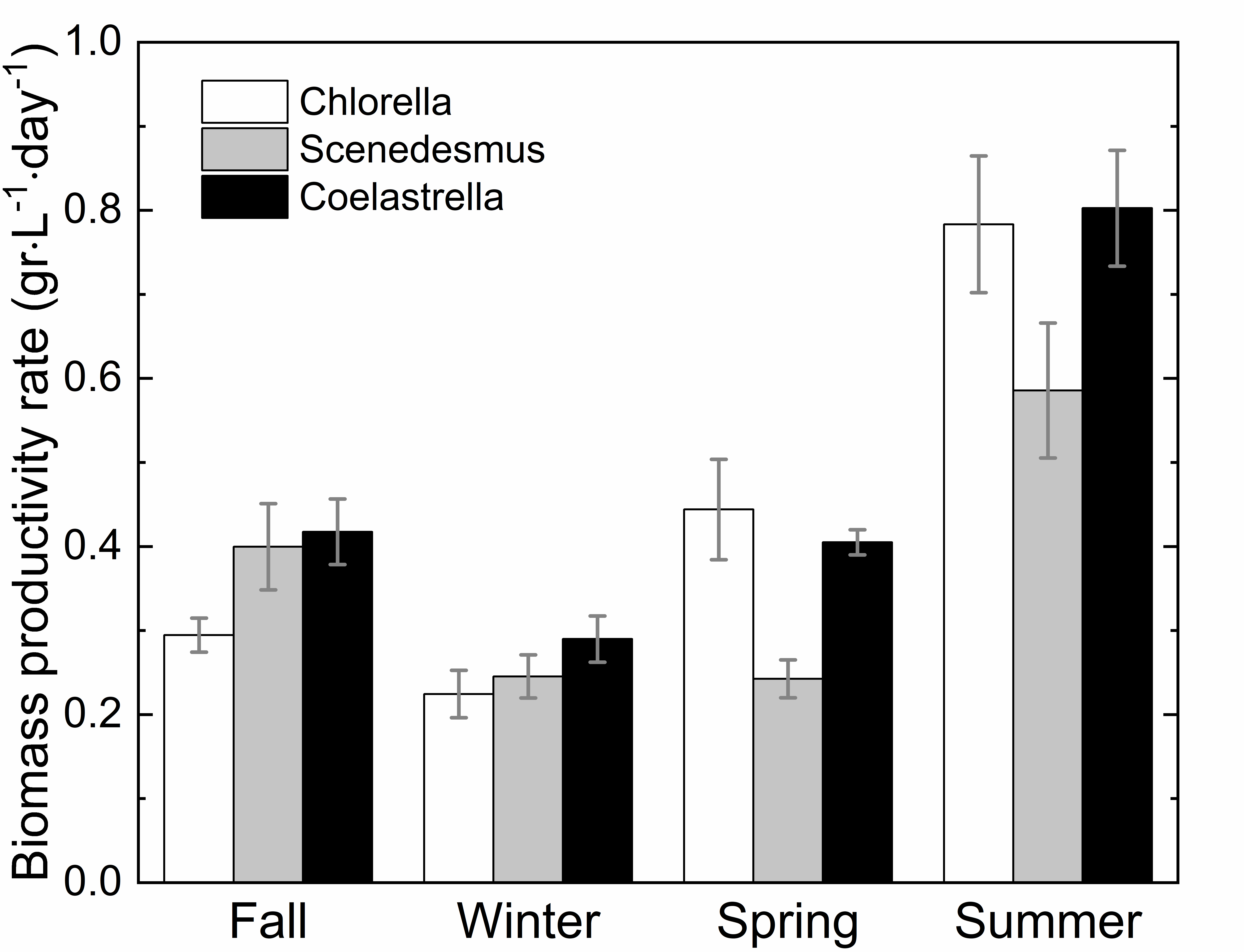


Fig.3. Average biomass productivity (n=3-4) of the three species during the four seasons calculated for the treatment times required to achieve TN <25 mg∙L-1 in the culture supernatant. Error bars indicate the standard deviation.

* + 1. Nutrients uptake

The average TN uptake and TAN uptake of the three strains during the four seasons are presented in Fig 4a and Fig.4b, respectively. The changes in the TN uptake for each strain between seasons correlated with the changes biomass productivity: the TN uptake of all strains was significantly higher (p<0.05) in summer compared to the TN uptake in spring and winter (besides *Scenedesmus* that had similarTN uptake between winter and summer) but not compared to the TN uptake in fall (p=0.5). In addition, no significant differences in the TN uptake were found between the three strains at each season. The average TAN uptake (Fig. 4b) was similar to the TN uptake besides *Scenedesmus sp.* that had a similar TAN uptake in all seasons (with a marginally significant higher uptake (p=0.08) in summer than in spring). In addition, the TAN uptake of *Chlorella* *sp*. was marginally significantly higher than that of *Scenedesmus sp.* during summer (p=0.09). The TN and TAN uptake results for each strain corroborate with the effects of the grwoth seasons and water characteristics that were found for biomass productivity. The differences in the TAN uptake between *Chlorella* and *Scenedesmus* also support the assumption that the desert-isolated strain performance was slightly better than that of the cold-climate-isolated strain, i.e., strain-related effects.



Fig. 4: The average TN (a) and TAN (b) uptakes of the three species in the four seasons. The uptakes were measured until the TN concentration was lower than the required concentration for unlimited irrigation in Israel (TN<25 ppm). Error bars indicate the standard deviation.

The average TP uptake rates are presented in Fig. S5. No significant differences in the TP uptakes were recorded between the strains at a specific season and for each species between the seasons. This is because the TP was fully consumed by all three strains within the first two days of cultivation in all seasons. The high TP uptake was recorded even during spring, despite the less favorable growing conditions. This highlights the efficiency of the system to recover phosphorus. As mentioned before, the TP was exhausted long before the TN during all growth periods. Nevertheless, the microalgae biomass continued growing and TN measured uptakes (until TN<25 ppm) were not affected by the low TP concentrations (Fig. 2 and Figs S1-3). Microalgae growth following TP depletion was demonstrated by others and was explained by the ability of the microalgae to accumulate P in the cell and slowly utilize it during the growth cycle (Shilton, 2014; Xiong et al., 2017). The very low P concentration also helps potentially to reduce mm

mv (ref)

The DOC in the effluent before and after cultivation was also measured. As expected as the tested microalgae do not produce and do not take up organics the DOC did not change following the microalgae cultivation and remained between 30 to 40 mg∙L-1 (which can be slightly higher than the standard required for irrigation 30 mg∙L-1 DOC).

* 1. *Mass balance*
     1. Water balance

One of the main challenges of microalgae cultivation under desert climate when the main goal is producing clean effluent is water evaporation and temperature. The water evaporation can be limited using PBRs and condensation-based cooling systems. However, this is practical when high-value products are produced due to high energy costs (Gupta et al., 2015). One peculiarity of the growth system applied in this study is the placement of column reactors with 40 cm culture height into a water pond of similar depth, whereby the water of this pond is cooled (and heated in winter) by heat exchange with a below-ground reservoir as a temperature buffer. On average, pumping action was required only for about 2 hours for cooling during summer (see Fig.1) pumping was applied for up to 60 minutes for heating (to keep early morning temperatures above 10˚C) during the winter. The application of the system allowed less than 15% evaporation effluent, mainly due to evaporation from the cooling pond. As a control, in summer, almost 40% of water loss was measured in a similar column that was placed outside the water bath, and 30% in a column soaked in a water bath but without circulation. The circulation also facilitated maintaining effluent temperature bellow 35 °C during summer while the effluent temperature in the dry control column was up to 55°C and approx. 40°C in the soaked uncirculated column.

3.2.4. C, N and P balance

Need to be added

* 1. *System performance and perspective*

The combination of the AnMBR as the biological treatment with microalgae as a post-treatment produced high-quality effluent from food-processing wastewater that contained up to 200 mg∙L-1 TN. Including the HTC in the treatment scheme enabled recovering most of the N, C, and P resources as high-quality microalgae biomass, biogas, and hydrochar. The virtually sterile AnMBR effluent inhibits the growth of heterotrophic microorganisms. Microscopy imaging of the microalgae taking during the summer growth season (Fig. S6) demonstrated that the microalgae cultures remained essentially free of fungi and protists contamination and had very low bacterial contamination. It also shows that a mono-algal form was maintained, which is an existential necessity for future applications during the long-term operation.

The proposed system succeeded in increasing microalgae biomass productivity sufficiently to allow for the continuous outdoors effluent remediation year-round. However, the system did not reach its theoretical optimum performance (biomass growth and nutrients uptake) in all seasons, as demonstrated by the similar performance between the microalgae species isolated from different climate regions, and the relatively low performance in spring. This illustrates that in the case of an uncontrolled outdoor microalgae cultivation system that treats real wastewater online monitoring and adjustment of key limiting elements (such as TP, N to P ratio, irradiation, etc.) is an important management tool that can enhance the system performance (González-Camejo et al., 2019b). It is also noted that other considerations rather than biomass growth and nutrients uptake may be taken into account when balancing the system flows throughout the year. For example, during the summer, the system can run for 4-5 days yielding higher amounts of microalgae biomass with 100% of TN and TP recovery (compared to 85% TN recovery as was done in this study) at the expense of an additional 20-30% of water lost to evaporation. In the winter, the dilution for each cycle can be lower to obtain the desired TP and TN recovery at a similar HRT as in the summer. Moreover, the choice of strains might also be influenced by the planned use of the resulting microalgae biomass. For example, in our previous study *Chlorella* had higher average protein content useful as feed, while *Coelastrella* had higher omega-3 fatty acid content (Belete et al., 2019) and can also produce high-value products when exposed to extended nutrient starvation under selected conditions (Pancha et al., 2014). Thus, an overall process performance should balance between the valued valorization of the resulting microalgae biomass and the amount and quality of the treated water produced. Ultimately detailed environmental and economic assessments, as well as site-specific market and other cost or system relevant details, must be considered to obtain a continuously operating zero-emission low-cost system. A realistically scaled pilot operation is also required to allow for the necessary assessments and market development.

# Conclusions (100 words)

A promising near-zero waste discharge scheme for food-process WWT is presented. High TOC fraction was removed using the AnMBR and was largely recovered as biogas. Excess AnMBR sludge was treated by HTC. The nutrients in AnMBR effluent were recovered by outdoor microalgae cultivation. The biomass productivity and TN and TP uptakes varied between the seasons due to unfavorable climate conditions or N to T ratio but with little differences between the three tested strains. The effluent quality for reuse was attained within 2 and 5 days in summer and winter, respectively. Mass balance analysis demonstrated a near-complete carbon and nutrients recovery and high water recovery.

## Declaration of Competing Interest

The authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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