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# Microalgae production cost in aquaculture hatcheries

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ABSTRACT

Microalgae are a crucial part in many aquaculture feed applications processes, mainly in hatcheries. Many aquaculture hatcheries maintain a small scale microalgae production facility in-house for the production of live feed. Microalgae are usually grown in non-automated bubble-column systems at unknown production costs. Other reactor systems or scenarios utilizing artificial light or sunlight and at different scales could result in a more cost efficient production processes. To determine the cost-price and cost-distribution of microalgae production facilities in Dutch aquaculture industry and identify the most efficient cost reducing strategies a techno-economic analysis for small scale microalgae production facilities (25-1500 $m^2$) was developed. Commercially available reactors commonly used in aquaculture were compared; tubular photobioreactors (TPBR) and bubble-columns (BC) in two placement possibilities; using artificial light in an indoor facility (AL) and utilizing sunlight in a greenhouse (GH) under Dutch climate conditions. Data from commercial microalgae facilities in the Netherlands are used to model reference scenarios describing the cost price of microalgae production with state of the art technology in aquaculture for a biomass production capacity of 125 kg $year^{-1}$. The reference cost price for algae biomass (on the basis of dry matter) is calculated at €290,- $kg^{-1}$ and € 329 $kg^{-1}$ for tubular reactors under artificial light and a greenhouse, respectively and €587,- $kg^{-1}$ and €573 $kg^{-1}$ for bubble-columns under artificial light and a greenhouse, respectively. The addition of more artificial light will significantly reduce production costs (by 33%) in all small-scale systems modelled. Biomass yield on light ($Y_{x,ph}$) showed the largest effect on cost price when not considering a different scale of the production process. Process parameters like temperature control should be aimed at optimizing $Y_{x,ph}$ rather than other forms of cost reduction. The scale of a microalgae production facility has a very large impact on the cost price. With state of the art technologies a cost price reduction of 92% could be achieved by changing the scale from 25$m^2$ to 1500$m^2$, resulting in a cost price of €43,- $kg^{-1}$, producing 3992 kg $year^{-1}$ for tubular reactors in a greenhouse. The presented techno-economic model gives valuable insights in the cost price distribution of microalgae production in aquaculture. This allows to focus research efforts towards the most promising cost reduction methods and to optimize existing production facilities in aquaculture companies to achieve economically sustainable microalgae production for live feed in hatcheries.

## 1. Introduction

In the past decade the use of microalgae for aquaculture has increased because of the importance of microalgae for the quality aquaculture feed (Borowitzka, 1997; Conceição et al., 2010; Shields and Lupatsch, 2012; Shah et al., 2018). The primary source of nutrition for all stages of filter-feeder bivalves and the larval and juvenile stages of fish is microalgae (Renaud et al., 1994; MullerFeuga, 2000; Brown et al., 1997). The quality of feed is linked to mortality rate of fish larvae, development rate, egg viability and reproductive success of copepods among others (Abate et al., 2015; Knuckey et al., 2005). It has been shown that using fresh microalgae as feed for oysters leads to higher product quality than what is achieved with processed algae products such as algae paste or flocculates (Knuckey et al., 2006). In addition, literature describes multiple examples where the positive effect of fresh microalgae is more pronounced when feeding a mix of

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*Abbreviations:* AL, Artificial light; GH, Greenhouse facility utilizing sunlight conditions; BC, Bubble-column photobioreactor; TPBR, Tubular photobioreactor; $Y_{x,ph}$, Biomass yield on light (g $mol^{-1}$); PFD, Photon flux density (mol $m^{-2}$ $day^{-1}$); OPEX, Operational expenditure; CAPEX, Capital expenditure

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different algal species. Combining multiple different species of freshly produced algae can create an optimized nutritional composition for the use in aquaculture (Brown et al., 1997).

For a constant supply of fresh microalgae, aquaculture hatcheries generally have an in-house microalgae production facility, which are generally small in scale, up to 100m$^2$. These small-scale production facilities traditionally consist of bubble-column type reactors (specifically the SEACAPs reactor systems). Recently, more complex, tubular photobioreactor systems have become readily available and have replaced bubble-columns in some aquaculture microalgae production facilities. Maintaining a microalgae production facility has been estimated to account for an average of 30% and up to 60% of the total budget of aquaculture hatcheries and nurseries as found in a study by Coutteau and Sorgeloos (Coutteau and Sorgeloos, 1992). This study estimated the cost of microalgae biomass in aquaculture hatcheries at 50–400 USD kg$_{DW}$ $^{-1}$ depending on the applied scale. These numbers were estimated based on numbers provided by employees operating microalgae cultivation systems in aquaculture applications in The United States of America through a questionnaire in the early 1990s. Despite the high cost prices, no effort has been described in literature to determine the cost price of microalgae in detail and highlight strategies for cost reduction. Microalgae production systems in aquaculture are typically not selected or optimized for a cost efficient production. The type of production systems used (bubble-columns or tubular reactors) in aquaculture usually represent regional or historical preferences (Shields and Lupatsch, 2012). A reduction of microalgae production cost could improve cost-efficiency and therefore viability of aquaculture companies/hatcheries. Other than the study by Coutteau and Sorgeloos (1992) no studies are found in literature focussing on calculating and reducing microalgae production costs for aquaculture or optimizing cost efficiency of microalgae production in small-scale production facilities. Most studies available in literature on microalgae for aquaculture applications focus on the nutritional value of the algae only.

Although algae have gained interest in research and commercial applications in recent years, a techno-economic analysis of small scale algae production facilities such as the systems applied in aquaculture is not available. Most techno-economic analyses for microalgae production are performed on much larger scales, focussing on the production of bulk chemicals and commodities such as biofuels (Norsker et al., 2011; Ruiz et al., 2016; Acién et al., 2012; Chauton et al., 2015). Although these studies show the opportunities and bottlenecks of large scale microalgae production, the costs distribution for small scale aquaculture applications will most likely be very different and cost reduction will require different strategies. In addition to scale, the use of artificial light in a closed environment and/or the use of a greenhouse are common practices in aquaculture but have never been analysed in previous techno-economic studies, which focus on outdoors production using sunlight.

In this study we aim to evaluate production costs and cost distribution of microalgae production in aquaculture hatcheries and provide guidelines for future cost reduction strategies. This is done by developing a new techno-economic model for microalgae production for the scale and production systems as found in this sector and performing a sensitivity analysis.

First, four commercial reference scenarios were created to closely resemble current microalgae production systems in the Dutch aquaculture industry. These scenarios set the base line for the current production costs of microalgae in this sector and allow pinpointing the parameters with major contribution to the cost price. These scenarios are further referred to as the reference scenarios. Secondly, a sensitivity analysis was performed by changing each input parameter individually and assessing the impact on the production costs and cost distribution. This was done to determine what strategies could result in the highest cost price reduction for aquaculture. Finally, the effect of scale of the production facility is assessed in more detail by comparing nine scenarios with production scales ranging from 25m$^2$ to 1500m$^2$.

**Table 1**
Summary of input parameters and their input values as used for the reference scenarios. All input parameters are set based on industrial standards using the biomass yield on light as determined for each scenario. The area of the production facility is adjusted to reach a total biomass capacity of 125 kg year$^{-1}$ for all scenarios. AL: Artificial light, GH: Greenhouse, BC: Bubble-column, TPBR: Tubular photobioreactor. The artificial light use is described by the type of light used, the hours of light applied per day and the total number of lights used per reactor (lights bubble-column bag$^{-1}$), in case of the bubble-column system, or the number of lights per m$^2$ (units m$^{-2}$) for the tubular reactor systems.

| | | AL | | GH | |
|---|---|---|---|---|---|
| | | BC | TPBR | BC | TPBR |
| Area of production facility | m$^2$ | 30 | 20 | 50 | 35 |
| Artificial lights | Type | TL-D 58 W | TL-D 58 W | None | None |
| Total artificial day length | hr day$^{-1}$ | 24 | 24 | 0 | 0 |
| Lights bag$^{-1}$ / Units m$^{-2}$ | # | 3 | 8 | 0 | 0 |
| Temperature range | °C | 20 | 20 | 15–25 | 15–25 |
| Algae-season start | Day | 1 | 1 | 1 | 1 |
| Algae-season end | Day | 365 | 365 | 365 | 365 |
| Lifetime of a culture | Days | 75 | 75 | 75 | 75 |
| Biomass yield on light | g mol$^{-1}$ | 0.22 | 0.45 | 0.32 | 0.45 |

## 2. Materials and methods

A techno-economic model was developed to describe algae production costs in aquaculture hatcheries in the Netherlands. A short description of the techno-economic model is given here. A more detailed description of the model can be found in the supplementary files section A.

It is assumed that the produced microalgae are utilized by the facility to directly feed marine organisms such as filter feeders without separating algae from the water stream after leaving the bioreactor. No harvesting or downstream processing steps are therefore considered. The techno-economic model uses a set of input parameters to calculate the production costs and cost distribution, among other outputs. An overview of selected inputs is described in Table 1. The total biomass production is calculated based on the total available light, photon flux density (PFD – mol m$^{-2}$ day$^{-1}$) and the efficiency of light utilization, i.e. the biomass yield on light ($Y_{x,ph}$ – g mol$^{-1}$). The total cost for production is calculated using the capital expenditure (CAPEX) and operational expenditure (OPEX) required for purchase and operation of the microalgae production facility, respectively. CAPEX includes the investments for purchasing all major equipment and OPEX contains all operational cost such as labour, electricity and consumables. The total biomass production capacity is calculated in kg$_{DW}$ year$^{-1}$ and the total cost in € year$^{-1}$ resulting in a cost price of biomass in € kg$^{-1}$. Each parameter, as listed in Table 1 affects the biomass production cost by impacting the amount of produced biomass, the total cost or both.

### 2.1. Reactor type and placement

The types of reactor systems considered in this study are bubble-columns (BC) and tubular photo bioreactors (TPBR). Both systems are based on commercially available reactors applied in aquaculture; SEACAPs (bubble-columns) and LGem Gemtube™ (tubular photobioreactors). Each reactor system is modelled at two placement options; an indoor facility using artificial lights only (AL) and a greenhouse facility using only sunlight (GH). This results in a total of four possible scenarios, a schematic representation of these four options is shown in Fig. 1. The calculated results are specific to the specified commercially available reactor types used in the techno-economic model.

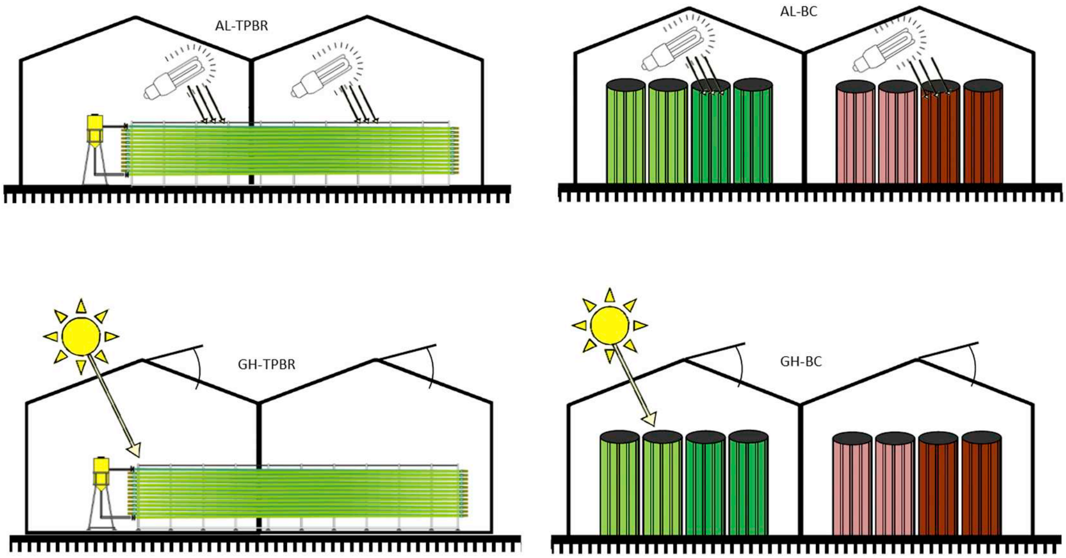

**Fig. 1.** Schematic representation of the four reference scenarios applied in the model. AL: Artificial light, GH: Greenhouse, TPBR: Tubular photobioreactor and BC: Bubble-column

### *2.2. Reference scenarios*

Industrial reference scenarios were established based on input from the producer and users of microalgae production systems in aquaculture. Two scenarios, GH-BC and AL-BC, were monitored for over 1.5 years for the collection of data on $Y_{x,ph}$, labour requirements, produced amount of biomass and energy requirements. The equipment used in these scenarios and data obtained from the monitoring of these systems was used to determine the inputs for the reference scenarios in the techno-economic analysis.

The production capacity of all reference scenarios was set at 125 kg year$^{-1}$ as based on the Dutch aquaculture reference scenarios. This biomass production capacity was achieved for each of the calculated scenarios by only adjusting the size of the facility (m$^2$) with set values for the total available light and biomass yield on light ($Y_{x,ph}$) used in each scenario, see Table 1. The total artificial light available was set at 580 µmol $m_{ground}^{-2}$ s$^{-1}$ for the two AL scenarios, based on data from industry. Due to restrictions in reactor size, this method of scenario creation has led to minor deviations in total biomass production (125 ± 10 kg year$^{-1}$) between the reference scenarios. The lifetime of a culture, the production period between starting and cleaning a reactor, was determined from the monitoring data and is different for each scenario. The total available sunlight for GH-scenarios was based on meteorological data for a typical meteorological year for Vlissingen, The Netherlands (Meteonorm 7.3.0). It is assumed that microalgae production is performed all year round for all reference scenarios. The temperature was set at a fixed value of 20 °C for the AL-scenarios. A temperature range of 15–25 °C was used for GH-scenarios.

### *2.3. Biomass yield on light*

BC-systems operated in aquaculture industry were monitored for over 1.5 years to obtain reliable estimates for $Y_{x,ph}$ for the reference scenarios. The average $Y_{x,ph}$ for the BC-systems was 0.22 g mol$^{-1}$ for AL-BC and 0.32 g mol$^{-1}$ for greenhouse placement (GH-BC) (for details see supplementary files section A1.3). For TPBR reference scenarios the $Y_{x,ph}$ was estimated from data obtained from the AlgaePARC pilot facility data available in literature (de Vree et al., 2016). The $Y_{x,ph}$ for the reference scenarios using TPBR-systems is set at 0.45 g mol$^{-1}$. The same value was used in both placements (AL and GH) for TPBRs.

### *2.4. Sensitivity analysis*

A sensitivity analysis was performed to determine the effect of the different parameters on the cost price of biomass. A total of seven changes were tested on each of the four reference scenarios. The seven changes are: 1 available light, 2 temperature range, 3 biomass yield on light increase ($Y_{x,ph}$), 4 reduced downtime, 5 reduced labour requirements, 6 seasonal production of algae and 7 a combination of scenarios 1–5. A summary of the changed parameters and the applied values can be found in Table 2. To investigate the effect of each parameter individually, each parameter was changed separately while keeping all other parameters identical to the reference scenario. The parameter with the largest impact on cost price (scale) was not included in the main sensitivity analysis but is investigated in more detail separately.

### *2.5. Sensitivity analysis inputs*

The available light is doubled for the artificial light scenarios from 580 µmol/m$^2$/s (reference scenarios) to approximately 1200 µmol/m$^2$/s (sensitivity analysis). The available light in greenhouse scenarios is changed by applying additional artificial light in the hours of the day with low sunlight availability during the first and last 1,5 light hours of each day. The artificial light is applied to create a total period of light availability of 20 h per day. The artificial light is applied from 1.5 h

**Table 2**
Changes made to individual input parameters for each of the seven sensitivity analysis scenarios. AL: Artificial light, GH: Greenhouse, TPBR: Tubular photobioreactor and BC: Bubble-column.

| | Parameter changed from reference scenario | AL | | GH | |
|---|---|---|---|---|---|
| | | BC | TPBR | BC | TPBR |
| 1. Additional AL | Lights bag$^{-1}$ / Units m$^{-2}$ | 6 | 16 | 2 | 5.5 |
| 2. Temperature range | Temperature range (°C) | – | – | 10–30 | 10–30 |
| 3. $Y_{x,ph}$ + 66% | Biomass yield on light ($Y_{x,ph}$) | 0.37 | 0.75 | 0.53 | 0.75 |
| 4. Reduced downtime | Lifetime of a culture (days) | 150 | | | |
| 5. Labor −33% | – | −33% total labor hours | | | |
| 6. Seasonal production | Algae-season Start/End day | 60–335 | | | |
| 7. Combined | – | Combined 1–5 | | | |

before sunset until 1.5 h after sunrise while maintaining a 4 h dark period in between. For GH-BC scenarios 2 TL-D 58 W lights were added per BC-reactor, as typically applied in aquaculture industry. For GH-TPBR scenarios, lights are added to reach an equal light intensity per unit floor area as for the GH-BC scenario (399 μmol $m_{ground}^{-2}\ s^{-1}$). The temperature range for greenhouse scenarios is increased from 15 to 25 °C to 10–30 °C. The temperature range was not changed for artificial light scenarios as these indoor scenarios are assumed to operate at a constant temperature in our calculations. The sensitivity analysis related to production season describes a scenario where the algae production facility is not operated during meteorological winter but only during the 60th until the 335th day of the year. The biomass yield on light ($Y_{x,ph}$) increased by 66% from the reference scenarios. Culture lifetime describes the length (in days) of operation of a reactor between inoculation and shutdown for cleaning procedures. The culture lifetime is doubled, from 75 days to 150 days. Labour is reduced by 33% to assess potential effects of automation on the cost price. Finally a combined scenario was created combining scenarios 1–5.

### 2.6. *Effect of scale*

The factor with the largest impact on cost price according to literature is the scale of production (Ruiz et al., 2016; Tredici et al., 2016). The effect of scale on small scale systems for aquaculture is assessed by comparing a total of 9 scenarios (the four reference scenarios, the 4 combined scenarios of the sensitivity analysis and a GH-TPBR-NoAL scenario) on 5 different scales each (25–100–250-750 and 1500m$^2$). The cost price of microalgae is evaluated as cost price per unit dry-weight (€ kg$^{-1}$) as a function of the total biomass capacity (kg year$^{-1}$) of the modelled scenarios to allow for direct comparison between the different systems.

## 3. Results and discussion

### 3.1. *Reference scenarios*

The results of cost price and biomass capacity for the reference scenarios in the techno-economic analysis are shown in Fig. 2. Detailed results and cost distribution can be found in supplementary files section 2.1. The lowest overall production cost for two placement options (GH and AL) is found with the TPBR-scenarios in both scenarios. A cost price of 290 € kg$^{-1}$ is found for the AL-TPBR scenario and 329 € kg$^{-1}$ for the GH-TPBR scenario. These results clearly show a cost price advantage for the TPBR-systems over the BC-systems in the reference scenarios. The BC-scenarios result in a cost price of 587€ kg$^{-1}$ (AL-BC) and 573€ kg$^{-1}$ (GH-BC). These cost prices are in the order of 100× higher than numbers described by Ruiz et al. but describe algae production on a much smaller scale then number described by Ruiz at 100 ha scale (Ruiz et al., 2016). The results correlate well with the findings of Sorgeloos who already described this much higher cost price of algal biomass on the small scale of aquaculture hatcheries (Coutteau and Sorgeloos, 1992; Ruiz et al., 2016). Even though the total cost price is similar between placements for each reactor system, the cost price distribution between CAPEX and OPEX shows differences between GH and AL scenarios for one reactor type. In the reference scenarios OPEX always contributes to the largest part of the cost compared to CAPEX; 82%, 74%, 78% and 60% for AL-BC, AL-TPBR, GH-BC and GH-TPBR scenarios respectively. As most of the cost price is attributed to OPEX, there is a large potential for cost-price reduction by reducing these operational costs. Adjusting operational procedures towards more cost efficient operation is considered more feasible than lowering the CAPEX for major equipment. Major equipment cost, contributing to most of the CAPEX, is expected to decrease with increasing microalgae facilities and newer technologies. However, this is not a factor that can be directly influenced by aquaculture orcurrent day microalgae production systems and it is therefore not considered in the cost price reducing strategies described in our study.

For the AL-scenarios, energy consumption contributes to a large fraction of the total cost price with 31% and 27% of the total cost price for AL-BC and AL-TBPR attributed to energy, respectively. In the corresponding GH-scenarios the energy component is a much smaller fraction of the total cost price (10% for GH-BC and 3% for GH-TPBR). The higher energy component for the AL-scenarios is the direct result of the electricity consumption of artificial light. Even though the energy use is significantly lower in GH-scenarios, almost the same cost price is obtained for the biomass when comparing the same reactor system in the AL and GH scenario. This is explained by the lower average biomass production rate found for the GH-scenarios due to the lower total amount of available light over a full year, resulting in a larger required reactor capacity for a biomass production of 125 kg year$^{-1}$. This results in an increased CAPEX for the GH scenarios and an increased OPEX, the latter mainly due to an increase in labour requirements per kg of biomass. These results indicate the economic feasibility of producing microalgae using artificial lights at the small scale for aquaculture whereas the use of artificial light at large scale is typically regarded unfeasible (Blanken et al., 2013).

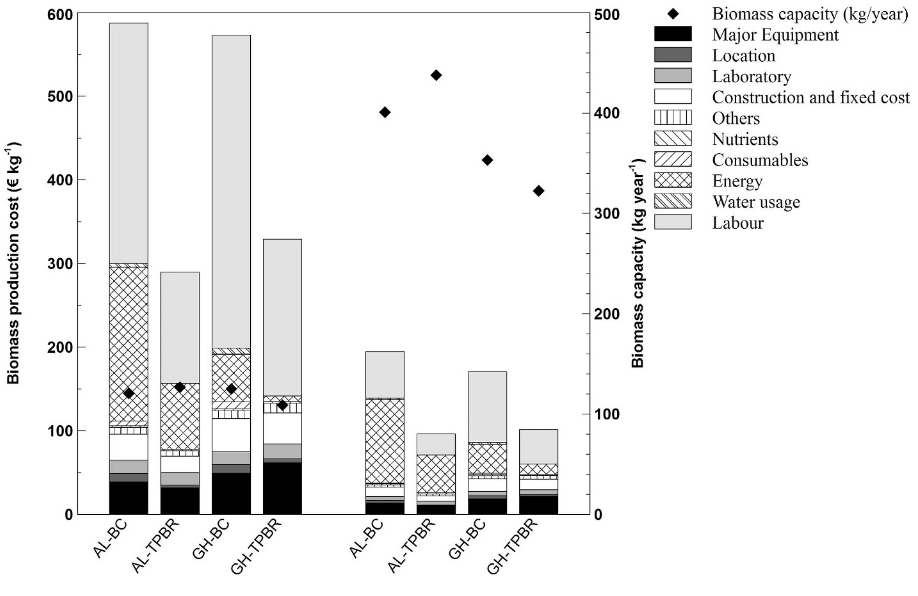

**Fig. 2.** Cost price of microalgae production, divided over 10 categories. Left half: four reference scenarios. Right half: combined scenarios from the sensitivity analysis excluding the effect of scale (bars – primary axis - € kg-1). Total biomass capacity of each scenario (kg year-1) is represented by the diamonds (secondary axis). At scales of 20-50m2. AL: Artificial light, GH: Greenhouse, BC: Bubble-column and TPBR: Tubular photobioreactor.

The lowest cost price for the reference scenarios is found for the TPBR-systems for both reactor placements. Tubular photobioreactors result in 51% and 43% lower production costs than the AL-BC and GH-BC scenarios, respectively. This result is somewhat surprising as TPBRs are generally regarded as more complex and more expensive than the simpler BCs. Our results can be explained by the way these systems are implemented in the aquaculture industry. The initial investment of a BC-facility is, in our model, approximately 2.200 € $m^{-3}$ of reactor volume excluding additional equipment. A TPBR production facility as modelled in the reference scenarios has 1 or 2 reactors with an investment cost of 28.000 € $m^{-3}$. The reference TPBR-scenarios require a total investment of €143.321 and €217.443 in the AL and GH settings, respectively. The initial investment of the reference BC-scenarios is higher for these scenarios (€183.001 and €232.364 respectively). Comparing the investment required per reactor volume the BCs appear much cheaper, but the total investment required for equal biomass capacity, as used in our reference scenarios, results in higher costs for in the BC-scenarios. The total reactor volume required for the AL-BC systems is 24 times larger than for the AL-TPBR application and for the GH-BC scenarios 20 times larger than for the GH-TPBR. This large difference in required volume is the direct effect of the differences in reactor design and is typically overlooked when comparing different reactor systems without applying a techno-economic analysis. In the reference scenarios the BC-scenarios are modelled with a lower $Y_{x,ph}$ (g $mol^{-1}$) than the TBPR-scenarios, resulting in a lower biomass production rate (g $m^{-2}$ $day^{-1}$) on equal amounts of light (mol $m^{-2}$ $day^{-1}$). This lower $Y_{x,ph}$ is the result of a larger light path, applying lower biomass concentration and the lower level of control in the BC-system. The lower $Y_{x,ph}$ of BCs compared to TPBRs means that a much larger reactor volume is required for BCs to obtain equal biomass production (kg $year^{-1}$). Reference scenarios are compared on equal biomass capacity rather than reactor volume or size of the production facility to allow for a fair direct comparison of the biomass production cost highlighting the difference in required reactor volume for equal production capacities.

Even though the calculations here show that BC-systems a more expensive method for algae production, the BC-systems are used in most aquaculture companies. Aquaculture often requires multi-species diets for feed applications (Brown et al., 1997). A multi-species diet cannot be achieved with a facility of one or two reactors as described in the TPBR reference scenarios, but is easily achieved with a modular reactor such as the BC-systems. The modular nature of the BC-systems also allows diversity in production capacity for the different species if required. In addition, operating a small number of reactors in a TPBR scenario represents a higher risks of losing the production when one reactor needs to be shut down for maintenance or cleaning. These reasons could explain the preference of aquaculture to maintain biomass production from BC-systems over TPBR-systems despite the difference in cost price.

To assess a multi-species production using TPBR-systems a scenario was tested with equal biomass capacity but with more, and therefore smaller, tubular reactors under artificial light. This results in a scenario with 7 × 250 l reactors compared to the single 750 l system applied in the AL-TPBR reference scenario. A larger total reactor volume is required to obtain the reference biomass capacity of approximately 125 kg $year^{-1}$ due to differences in reactor lay-out between the 250 l and 750 l systems. Results showed a production capacity of 134 kg $year^{-1}$ at €606 $kg^{-1}$. Showing slightly higher cost prices than the BC-system in the reference scenario (121 kg $year^{-1}$ at €587 $kg^{-1}$ for AL-BC) indicating an advantage for BC-systems when a strict multispecies diet is required on this small scale. Moreover, BC-systems have been common practice for algae production in aquaculture hatcheries for many years whereas TPBR-systems have only become commercially available recently.

The price advantage found for the TPBR-systems in the reference scenarios could be partially due to the selected inputs used. The selected biomass yield on light ($Y_{x,ph}$) for TPBR-systems is higher than for the BC-scenarios. To test the impact of the biomass yield on light, the $Y_{x,ph}$ of the AL-TPBR reference scenarios was decreased from 0.45 to 0.22 g $mol^{-1}$, the lowest value applied for BC-systems. The decrease of $Y_{x,ph}$ was combined with an adjusted floor area (from $25m^2$ to $40m^2$) to result in an equal total biomass capacity as the reference scenarios (124 kg $year^{-1}$). A scenario with one 1500 l reactor shows a biomass production cost of €401 $kg^{-1}$ whereas a scenario of 2 × 750 l reactors results in a cost price of €438 $kg^{-1}$ at this low value for $Y_{x,ph}$. When operating a fully controlled TPBR in a commercial setting the low value for $Y_{x,ph}$ (0.22 g $mol^{-1}$) is unlikely, especially in a highly controlled setting as described in the AL- scenarios. Nevertheless, this comparison shows that at equal biomass production capacity (124 and 121 kg $year^{-1}$) and equal $Y_{x,ph}$ (0.22 g $mol^{-1}$) the cost price of biomass in the TPBR-systems is lower than for BC-scenarios. This shows that even when operating at low $Y_{x,ph}$ the TPBRs yield the most cost efficient production strategy even though the disadvantage of not having a multispecies diet remains.

### 3.2. Sensitivity analysis

The results of the sensitivity analysis display the effect of each input parameter on the cost price. The results of cost price reduction (in % from the reference scenarios) are presented in Fig. 3, with more detailed values for the combined scenarios (7) available in Fig. 2 and the supplementary files section 2.2.

### 3.3. Additional artificial light

The results in Fig. 3 show that additional artificial light has a large impact on the cost price for all systems. A cost price reduction in biomass production is found for all four scenarios with additional artificial light. Doubling the artificial light in AL-scenarios doubles the total biomass production per year while adding costs for the lights in both CAPEX and OPEX. This results in a total production cost of €375 $kg^{-1}$ (a reduction of 36%) for AL-BC) and as production cost of €188 $kg^{-1}$ (a 35% cost reduction) for AL-TPBR. An equal cost price reduction is found for the GH-scenarios: 36% and a cost price of €364 $kg^{-1}$ for GH-BC and 35% with a cost price of €212 $kg^{-1}$ For GH-TPBR. For the GH-scenarios the total biomass output is increased by 70% and 72% for the GH-BC and GH-TPBR scenarios, respectively, instead of doubled as for the AL-scenarios. Even though the biomass output is not doubled the same percentage cost price reduction is found.

Blanken et al. described that the use of artificial lights is too expensive for microalgae production from a perspective of bulk chemical production (Blanken et al., 2013). The added cost for the use of artificial light in aquaculture applications however does result in a cost reduction for all reference scenarios, due to the high initial biomass production cost price on the small scale applied. Even though the additional artificial light increases the total CAPEX and OPEX, a cost price reduction is obtained due to the large increase in total biomass output. The additional cost for the added artificial light is low compared to cost price of biomass in the reference scenario. The OPEX of artificial light per unit biomass is a function of the biomass yield on light ($Y_{x,ph}$ – g $mol^{-1}$), the PAR efficiency of the light source (μmol $W^{-1}$) and the price of electricity (€ $kWh^{-1}$). The CAPEX of artificial light per unit biomass is a function of the cost price of the light source (€ $unit^{-1}$), the biomass yield on light ($Y_{x,ph}$ – g $mol^{-1}$) and the lifetime of the light source (hours) (Blanken et al., 2013). In our study the lights applied are TL-D 58 W fluorescent lamps with a PAR efficiency of 1.25 μmol $W^{-1}$ and a lifetime of 15.000 h and using the $Y_{x,ph}$ of the reference scenarios (0.22–0.45 g $mol^{-1}$). This results in a cost price for artificial lights between €86 and €42 $kg^{-1}$ biomass for the tested scenarios. The cost of artificial light is significantly more than the numbers described by Blanken et al. (2013) who describes additional cost of \$26.7 $kg^{-1}$ (approximately €21,- in 2013). The difference can be explained by the

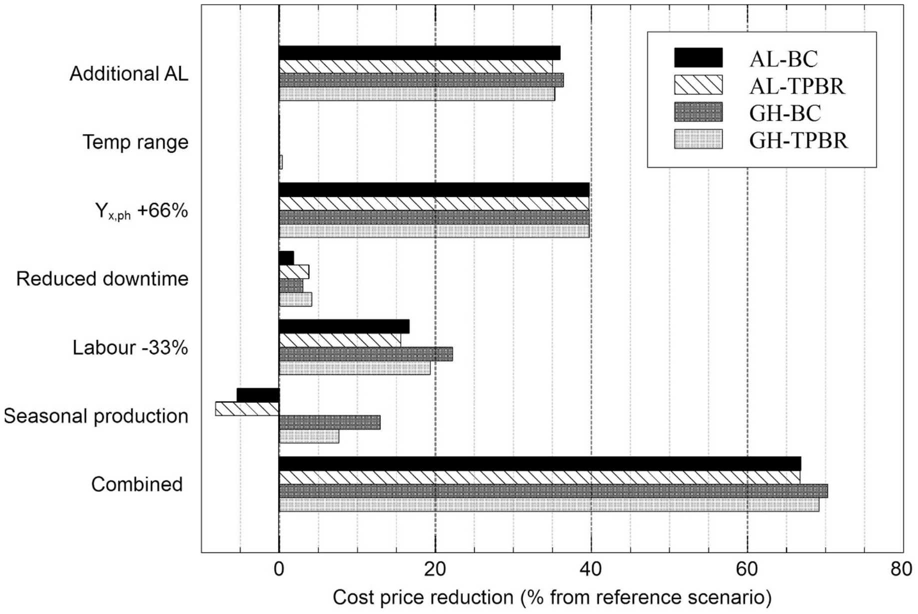

**Fig. 3.** Results of the sensitivity analysis; the effect on cost price, as a % in cost reduction from the reference scenarios for changes made to the scenarios. AL = Artificial light, GH = Greenhouse, BC = Bubble-column and TPBR = Tubular photobioreactor

differences in assumptions used. Blanken used an average PAR efficiency of 1.67 μmol $W^{-1}$, a lifetime of 50.000 h for LED lights and a $Y_{x,ph}$ of 1.0 g $mol^{-1}$ (compared to 0.22–0.45 g $mol^{-1}$ in our work) resulting in a lower price of artificial light per unit biomass.

The addition of artificial light can be regarded as an easy to implement and cost effective method for cost price reduction in existing microalgae production facilities in aquaculture if the reference cost price is higher than the cost of additional light. The use of highly efficient light sources such as LEDs, will make the use of artificial light even more economically interesting for small scale algae production than shown in our results.

In the scenario with additional light it was assumed that the $Y_{x,ph}$ remains unchanged from the reference scenarios. However, literature describes a negative correlation between light intensity and biomass yield on light for light conditions above light saturation conditions as applied in the reference scenario and the sensitivity analysis (Macintyre et al. 2002). Increased light intensities typically result in a lower photosynthetic efficiency. In reality the cost reduction by additional artificial lights could therefore be smaller than shown in the modelled AL-scenarios. Assuming a 25% decrease of $Y_{x,ph}$ for doubled light intensity scenarios (from 600 μmol $m_{ground}^{-2}$ $s^{-1}$ to 1200 μmol $m_{ground}^{-2}$ $s^{-1}$) shows a cost price decrease of 14–15% in the modelled scenarios, still showing the positive effect of more light. This effect will be different on GH-scenarios as for those scenarios the additional artificial light is added during dark periods and therefore does not double the incident light intensity on the algae cells.

### 3.4. Temperature range

The temperature range was only tested for the GH-scenarios. In AL-scenarios a constant temperature of the indoor facility is assumed and cooling requirements are based on heat production by the artificial lights. For the GH-BC scenario, reactors are not actively controlled for temperature and a change in the temperature range does therefore not affect the cost price. In the GH-TPBR scenario the temperature of the systems is actively controlled. The larger temperature range results in a reduced cost price, but only by a very small percentage at only 0.36% (€328 $kg^{-1}$). This result seems contradicting with literature as Ruiz et al. showed that temperature was one of the main influencing parameter on the cost price of biomass (Ruiz et al., 2016). Ruiz describes a 12% cost price decrease for a scenario with increased temperature tolerance (30–45 °C) for flat-panel PBRs located in the South of Spain. The cost price reduction for our calculations with increased temperature range is €1.20 $kg^{-1}$ from a base price of €329 $kg^{-1}$ (0.36%) where Ruiz described a cost price reduction of €0.40 $kg^{-1}$ on a base cost price of €3.40 $kg^{-1}$ (11.7%). The cost price reductions in € $kg^{-1}$ is of comparable order of magnitude between the different scenarios and the difference could be attributed to actual temperature range differences, location (solar input, wind speeds, etc.), electricity cost, reactor geometry and more. The cost reduction in our calculations is smaller due to the much higher cost price for biomass used as reference. Algae growth at temperatures other than the optimal growth temperatures will results in a negative effect on the biomass on light (Bernard and Rémond, 2012). It is therefore concluded to be more cost efficient on these small scales to optimize temperature control towards optimized $Y_{x,ph}$ rather than energy reduction.

### 3.5. Biomass yield on light

Biomass yield on light ($Y_{x,ph}$) has a large effect on the cost price as this directly impacts the total amount of biomass produced. The same effect of $Y_{x,ph}$ is found for all systems: by increasing the biomass yield on light, the total amount of biomass produced is increased without adding costs in our calculations. These results show the importance of operating a microalgae facility using optimized growth parameters and maximizing $Y_{x,ph}$. The $Y_{x,ph}$ found for the monitored systems (0.22–0.32 g $mol^{-1}$) is much lower than values available in literature. Examples in literature describe 0.75–0.80 g $mol^{-1}$ on experimental reactors (Zijffers et al., 2010), 0.79 g $mol^{-1}$ in pilot-scale TPBRs in Spain (Acién et al., 2012), and values in the range of 0.2–1.0 g $mol^{-1}$ in pilot-scale TPBRs in the Netherlands depending on reactor operation, dilution rate, biomass concentration and the photon flux density (De Vree et al., 2015; de Vree et al., 2016). The most relevant numbers for comparison are those described by de Vree et al. on a pilot plant TPBR-system under the Dutch climate. The systems described by de Vree are more advanced and were better controlled than the commercial BC-systems used for data collection, explaining part of the difference in $Y_{x,ph}$ described. De Vree describes data produced in reactor systems operated in chemostat or turbidostat at constant pH, monitored and controlled by computer systems. The commercial BC-systems operate without pH control in chemostat mode with a dilution rate that is manually adjusted per reactor. Nutrients are equal for all strains and adjustments are made manually rather than computer controlled. The gap between $Y_{x,ph}$ from literature and the monitoring data of commercial aquaculture systems indicates a large potential for improvement of the aquaculture production systems.

Literature describes how optimizing growth parameters can increase biomass productivity and biomass yield on light (Kim et al., 2012; Guevara et al., 2016). Optimizing growth parameters such as light and temperature for the species in use or adjusting the harvesting regime and nutrient addition can result in higher $Y_{x,ph}$ with limited or no additional cost. Operating at optimized growth conditions requires controllable reactor systems, favouring the AL-TPBR scenario. In such scenarios, each reactor can be operated at a different temperature, light intensity, pH, nutrient concentration and harvesting regime optimizing growth parameters for different species in one facility.

It has to be noted that solely aiming for the highest $Y_{x,ph}$ would not yield the most cost efficient system. Maximum $Y_{x,ph}$ is typically found at low light levels as was indicated in the data by de Vree (de Vree et al., 2016). Biomass production cost is a function of the total biomass capacity (kg) and total cost (€) of a production facility. Increasing $Y_{x,ph}$ should only be the aim if it leads to a larger total biomass production without substantially increasing operational cost. For each change to any scenario a breakeven for added cost (CAPEX and OPEX) vs additional biomass produced could be determined. Such breakeven scenarios requires complete understanding and quantification of the biological impact of any changes for the produced species. This biological information coupled to the techno-economic model could allow to determine the effect of specific changes of the operation parameters on the cost price in detail. Research focussed on understanding the algal species used in aquaculture application and optimizing the applied growth parameters for most cost efficient production is therefore one of the most promising cost reduction methods for small scale microalgae production but requires more effort than other cost reduction strategies.

### 3.6. Reduced downtime

The lifetime of a culture describes the production period that can be obtained between starting a new reactor and stopping the system to be cleaned. This parameter is only relevant for continuous systems as described in our modelled scenarios and does not apply to batch operation. Maintaining a culture for longer periods without cleaning the reactor systems reduces production cost price due to reduced labour requirements with increased biomass production as a result of the lower downtime. The results of a doubled culture lifetime (75 to 150 days) show a reduced production cost by 1.8% and 3.0% for the AL-BC and GH-BC scenario and 3.8% and 4.1% for the AL-TPBR and GH-TPBR scenarios, respectively. The largest impact of culture lifetime is found for TPBR-systems as the downtime for cleaning and restarting a new culture in TPBR-system is much larger than for BC-systems. The downtime for cleaning and batch operation to restart continuous operation of a TPBR system is set at 5 days. BC-systems are assumed not to have a downtime, as 10% of all bubble-columns is assumed to be used as inoculum production for the following run.

The relatively small effect of reduced downtime on the production cost can be explained by the relatively long culture life assumed in the reference scenarios. The reference of 75 days was determined as the average from the monitoring data of commercial AL-BC and GH-BC systems. The data showed a large variation for culture lifetimes ranging from 10 to 200 days for the same system between different reactor runs – this behaviour was observed for both the AL-BC and GH-BC reactors systems. With the large fluctuations in culture lifetime observed in the commercial systems used in our input data this parameter is more important that initially suggested by the modelled scenarios. In commercial applications it is found that a reactor usually significantly decreases in productivity and observed $Y_{x,ph}$ before a reactor is stopped for cleaning. This reduction of efficiency was also described by de Vree et al. who suggests inline cleaning of TPBR-systems could help prevent this loss of efficiency (de Vree et al., 2016). Our monitoring data showed that cultures that were recorded with shorter and longer than average culture lifetimes were linked to lower than average values for $Y_{x,ph}$, indicating a trade-off between maintaining a culture longer at a lower $Y_{x,ph}$ and cleaning a reactor to restart a new culture.

### 3.7. Labour

Labour is the largest cost price component for all reference scenarios, representing between 46 and 65% of total cost. The results of the sensitivity analysis with labour requirements reduced by 33% show a cost price reduction of 16.6% and 22.2% for the AL-BC and GH-BC scenarios and 15.6% and 19.4% for the AL-TPBR and GH-TPBR scenarios. The largest effect of reduced labour is found for the GH-scenarios as these scenarios describe systems containing a larger number of total reactors to reach the total biomass capacity of the reference scenario than their AL counterparts (80 reactors for AL-BC and 134 for GH-BC and 1 vs 2 TPBRs for AL-TPBR and GH-TPBR). More reactor capacity results in a larger labour requirement and therefore a larger effect of labour reduction on these scenarios is found. In practical applications reduced labour costs would typically be obtained by the implementation of more automation for example to harvesting, nutrient addition and artificial light systems, among others, typically linked to higher CAPEX which has not been regarded in the above calculations for cost reduction. A scenario with highly automated production facilities is more feasible for the TPBR-systems than for BC-system. TPBR-systems already have an automated pH and temperature control integrated but lack automatic harvesting. Applying an automated harvesting system to operate the reactors in turbidostat or chemostat mode would create more constant culture conditions, especially under artificial light conditions potentially also resulting in an increased $Y_{x,ph}$. A breakeven point between additional automation and labour reduction could be determined using the presented model, but would be different for every scenario.

### 3.8. Seasonal production

The scenarios in greenhouses under the Dutch climate show a very low biomass productivity in winter months due to the low light availability. The scenarios simulated with no production in winter show a reduction of the microalgae production costs of 12.6% and 7.9% for the GH-BC and GH-TPBR scenarios, compared to production during all days of the year. For AL-scenarios a cost price increase (negative effect on cost price) is found as lower total biomass capacity results in a larger cost component for the depreciation of major equipment per unit of biomass produced. The results for GH-scenarios do show a cost price reduction indicating that production costs during winter are significantly higher than the rest of the year. The costs for operation do not outweigh the small amount of biomass produced in these months. The modelled scenarios without production in winter shows a reduction of only 7.2% of the total biomass capacity compared to the reference scenarios (9 kg for GH-BC and 8 kg GH-TPBR) while reducing the operational time by 24.6%. In practice, microalgae are required all year round, most commercial application in aquaculture therefore apply artificial light when low levels of sunlight are available. The results of GH-scenarios utilizing additional artificial light are described in more detail in the artificial light section of the sensitivity analysis and showed a total cost price reduction of almost 40% while maintaining year round production.

### 3.9. Combined scenario

A scenario described a combination of additional artificial light, temperature range (where applicable), increased $Y_{x,ph}$, reduced downtime and reduced labour serve as an outlook on possible cost reductions for small scale aquaculture microalgae production facilities in the nearby future. The parameter seasonal production did not show a cost price reduction when combined with other parameter changes and is therefore excluded from the combined scenario. A total cost reduction of 67–70% compared to present practice can be obtained (see Fig. 2 and supplementary files section B2). This future outlook on small scale commercial systems shows a cost price of €96,- kg$^{-1}$ for AL-TPBR and €101,- kg$^{-1}$ for the GH-TPBR scenarios and €195,- kg$^{-1}$ and €170,- kg$^{-1}$ for AL-BC and GH-BC, respectively. Part of the cost price reduction is achieved by methods that increase the total biomass productivity of the system while other parameters directly impact the total cost of operation on these systems as described in their individual chapters. The results show that a very large cost price reduction could be achieved with the combined parameter optimization. It has to be noted that the combination of all these.

cost reduction methods combined might be difficult to obtain as combining more light, with lower labour requirement and an increased temperature range while achieving a higher $Y_{x,ph}$ could be challenging without additional costs.

### 3.10. Scale

The scale of an algae production facility has a large impact on the cost price. The total effect of scale on the cost price for each scenario is compared by comparing scenarios at equal floor area. The results for the effect of scale are summarized in Fig. 4, showing the cost price as a function of total biomass capacity (kg year$^{-1}$) for each of the scenarios. Detailed values for biomass production cost and biomass capacity for each scenario can be found in section B.4 of the supplementary files.

The results related to scale are highly dependent on the selected inputs from the starting reference scenario. Therefore, and because it is a parameter with a high impact, the effect of scale was analysed in more detail for a total of 9 scenarios. This analysis shows the potential cost price reduction that could be achieved when producing algae for multiple aquaculture facilities in one centralized algae production facility. Four scenarios show the cost price at different scales for the reference scenarios (solid lines in Fig. 4). The scenarios with combined optimization of the sensitivity analysis (1–5) are used for a future outlook on biomass cost price at larger scales (dotted lines in Fig. 4). Additionally a GH-TPBR scenario using the combined cost reduction methods from the sensitivity analysis is modelled without the addition of artificial light (GH-TPBR-NoAL) in order to indicate the breakeven point for the use of artificial light in a GH-TPBR scenario.

A large difference in the economy of scale of the two reactor types is found in the results of Fig. 4. The scalability is mostly dependent on the reactor type (BC vs TPBR) and not reactor placement (AL vs GH). Increasing the production capacity for both reactor types, has a different effect on the biomass cost price. For the BC-reactors an effect of the economy of scale is observed in the smaller sizes but this reaches a minimum cost price for the applied scenario and barely decreases with increased scale above 100m$^2$. The TPBR-scenarios keep decreasing the biomass cost price for each subsequent larger scales. For the BC-scenarios the total number of reactors increases linearly with increased ground area. The BC-reactors have an investment cost of €2.200 € m$^{-3}$ and this does not change with increased scale. The TPBR-systems are commercially available in different sizes with a steep decrease in investment per volume unit (€ m$^{-3}$) when moving to larger systems. The TPBR-systems considered in this model include reactor sizes of 250, 750, 1.500 and 18.000 l culture volume. Investment cost per volume unit of these systems ranges from 120.000 € m$^{-3}$ for the 250 l systems to 8.000 € m$^{-3}$ for the 18.000 l reactors.

Labour requirements scale differently for the reactor systems as a result of the way the reactor types scale up. Labour requirements for the BC-systems are defined to have a decreased average labour requirement per reactor scaling up to 160 reactors in our study. For more than 160 BC-reactors the labour requirements per reactor remain the same at 0.014 h reactor$^{-1}$ day$^{-1}$.

This amount of labour only includes normal culture maintenance, labour requirements for cleaning and culture replacement is calculated separately depending on culture lifetime. Labour requirements for the TPBR-systems is based on a fixed amount of hours of labour required reactor$^{-1}$ day$^{-1}$. TPBRs at the 250-1500 l scales require 0.25 h reactor$^{-1}$ day$^{-1}$ whereas the 18.000 l system requires 0.5 h reactor$^{-1}$ day$^{-1}$ for normal operation. The labour requirements for cleaning procedures for the 250-1500 l systems was set at 1.5 h

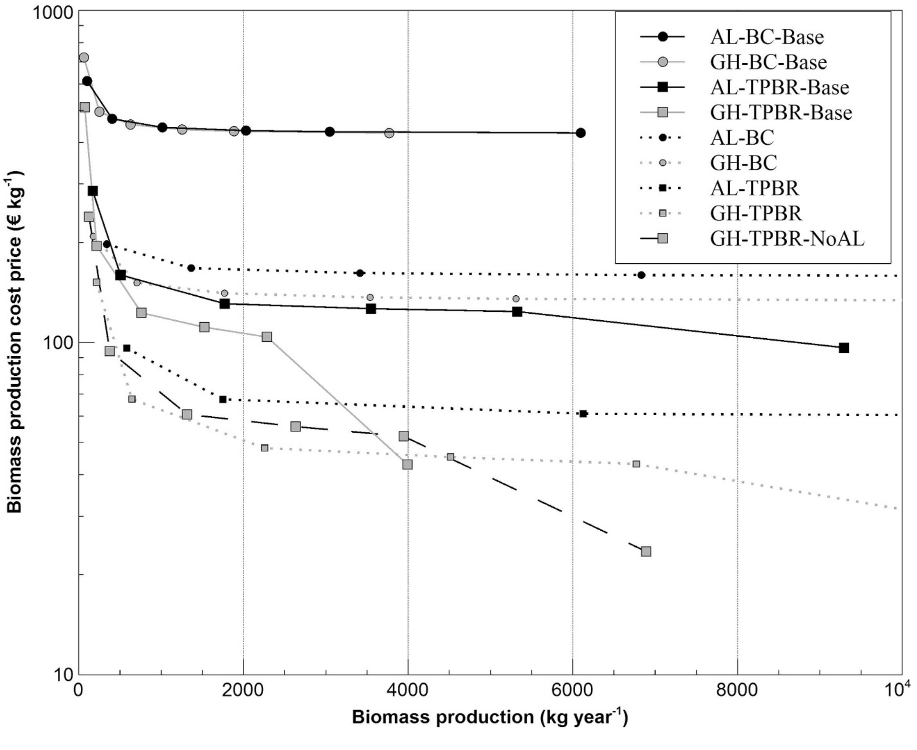

**Fig. 4.** Cost price of biomass (€ kg-1 y-axis, logarithmic scale) represented over the total biomass production (kg year-1 x-axis) of 9 different scenarios for 6 scales (25-100-250-500-750-1500m2), each subsequent marker represents the next scale size. Solid lines represent reference scenarios, dotted lines show scenarios described as combined scenarios of the sensitivity analysis. BC = bubble-columns (circles), TPBR = Tubular photobioreactors (squares), AL = artificial light (black), GH = Greenhouse (grey). GH-TPBR-NoAL represents the same scenarios as GH-TPBR with combined scenarios of the sensitivity analysis but without the addition of artificial light. For combined scenarios some scales produce more biomass than the maximum represented 10.000kg year -1; detailed numbers can be found in the supplementary files.

reactor$^{-1}$ per clean and for the 18.000 l system at 3.0 h reactor$^{-1}$.

The largest effect of scale for BC-systems is found for the smallest production facilities. A strong price decrease is found for scales increasing up to about 500 kg year$^{-1}$ (25-250 m$^2$). After an initial price decrease the BC-systems do not show a significant scale effect. It has to be noted that for the BC-systems large scale scenarios are not considered practically feasible and are only calculated to show the effect of scale. In real world applications it is not advised to operate a facility with more than 160 BC-reactors of the type specified in this study, due to practical difficulties and the high cost price associated to this system at large scale compared to other production methods available, as also shown in the results. The BC-systems, used in this study, are primarily designed as small scale production systems for use in aquaculture.

For TPBR-systems, scale-up significantly decreases biomass production cost. Comparison of all TPBR-scenarios at an equal biomass capacity of 4000 kg year$^{-1}$ shows the lowest cost price at the reference scenario for tubular reactors (GH-TPBR-Base in Fig. 4) at the largest tested scale (1500 m$^2$). This GH-TPBR-Base-1500 m$^2$ scenario describes 2 × 18.000 l reactors to produce biomass at €43,- kg$^{-1}$ using state of the art technology. The AL-TPBR scenario with combined optimization obtains an equal biomass capacity at the 500m$^2$ scale. This smaller scenario describes 14 × 1500 l reactors at a biomass production cost price of €45,- kg$^{-1}$. The comparison between these two scenarios shows the large impact scale has on the cost price in TPBR-systems. The same biomass production cost of approximately €45,- kg$^{-1}$ at a production scale of approximately 4000 kg year$^{-1}$ can be achieved with state of the art production systems using 18.000 l systems compared to the scenario using all cost reduction strategies combined using 1500 l reactor systems.

The results show that all TPBR scenarios on the 1500m$^2$ scale utilizing the 18.000 l reactors result in a large cost price reduction compared to the previous scales with 1500 l systems. The same pattern is found between scenarios utilizing the 750 l and 1500 l systems and all other steps with a change of reactor scale. This is the result of the steep decrease in investment cost per unit reactor volume and the decrease in labor requirement between operation of 2 or 14 reactors.

The overall lowest biomass production cost for the scenarios studied is found for the GH-TPBR scenarios not utilizing artificial lights (GH-TPBR-NoAL) on the largest scale (1500m$^2$) producing 6.892 kg year$^{-1}$ at €23,47 kg$^{-1}$. The addition of artificial lights on a larger scale under more optimized conditions yields higher biomass cost price while producing much more biomass (11.822 kg year$^{-1}$ at €26,35 kg$^{-1}$ for the GH-TPBR scenario). This shows that when moving to larger scales the addition of artificial light will not always result in a cost price reduction as it does for the small scale. At the 1500m$^2$ scale the cost of artificial light exceeds the relatively low cost price of biomass, supporting the results as described for the sensitivity analysis on additional artificial light.

Optimizing the scale of a microalgae production facility shows a big potential for cost reduction. The results show that for the reference scenarios the cost price could be reduced by 21–24% for BC-scenarios and 55–65% for TPBR scenarios by simply increasing the operation from the reference scenarios of 25-40 m$^2$ to 250 m$^2$ and much further when moving to 1500m$^2$. Most aquaculture applications do not require the amount of biomass that is produced at these scales. A specialized algae facility providing biomass for multiple aquaculture applications could produce at a larger scale, reaching much lower production prices than the smaller individual systems. The scenarios describing the lowest biomass production cost in this comparison, GH-TPBR-NoAL at €23,47 kg$^{-1}$ and GH-TPBR €26,35 kg$^{-1}$, produce 55-100× the biomass capacity as described in the reference scenarios for aquaculture. More realistic near term prediction can be found in the result for GH-TPBR-Base at 250m$^2$. This scenario describes a facility producing 762 kg year$^{-1}$ at €123,- kg$^{-1}$ without further improvements of state of the art technologies other than a scale increase.

## 4. Conclusion

The cost price of small scale industrial microalgae production facilities as presently used in the aquaculture industry was evaluated using a techno-economic analysis. Modelled scenarios based on current commercial standards showed that microalgae biomass cost prices are currently between €587 kg$^{-1}$ and €290,- kg$^{-1}$. Two of the most applied commercial systems were compared (bubble-columns vs tubular reactor systems) showing a significant price advantage for the tubular reactor systems in all tested scenarios. The potential for cost price reduction based on state of the art technology and operation can be significant, up to 90% cost reduction can be achieved from the reference scenarios. From the tested scenarios, the addition of artificial light, increasing $Y_{x,ph}$ and reducing labour requirements showed the largest potential for cost price reduction when not changing the scale of the production facility. For existing production facilities the easiest strategy for cost price reduction is the addition of artificial light, yielding a cost reduction of 35–36% for all tested scenarios. Other cost price reducing strategies should focus towards higher efficiency of the available production methods, thereby increasing the $Y_{x,ph}$. This could be achieved by optimizing growth parameters for the produced strains by optimizing temperature, light, pH, nutrient availability and harvesting strategies in the applied systems. Changes in temperature should focus towards improved growth rather than cost reduction for energy consumption.

The size of the facility shows the largest impact on the cost price of microalgae, but a larger scale could be difficult to implement in most existing facilities due to a lack of biomass requirements. A centralized microalgae production facility providing high quality microalgae for multiple aquaculture applications could decrease the cost price by 60–80% when producing 762 kg year$^{-1}$ at €123,- kg$^{-1}$ on a 250m$^2$ scale, compared to the 125 kg year$^{-1}$ in the reference scenarios. This larger scale is still considered to be a very small production facility, but does show a large reduction of overall biomass production cost. On an even larger scale (1500m$^2$) a cost price of €43,- kg$^{-1}$ is feasible with state of the art technology and future improvements can reduce this to €26,40 kg$^{-1}$ on the large 1500m$^2$ scale utilizing TPBR-systems. The large cost reduction that could be achieved in such a facility could have a large impact on aquaculture production processes in the future.

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## Author contributions

PCO, JvH, RHW and MJB conceptualization, Methodology, Supervision, Writing - reviewing and Editing. PCO Investigation, Formal analysis, Validation, Writing – original draft. All authors edited and approved the final manuscript.

## Declaration of Competing Interest

All authors agreed to the authorship and submission of the manuscript to Algal research for peer review.

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## Appendix A. Supplementary data

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