Implications of fundamental aspects of purple phototrophic bacteria for process upscaling

Gabriel Capson-Tojo, Damien J Batstone, Tim Hülsen

IWA World Water Congress & Exhibition
11-15 SEPTEMBER 2022 | COPENHAGEN, DENMARK | www.worldwatercongress.org

Implications of fundamental aspects of purple phototrophic bacteria for process upscaling

G. Capson-Tojo*,, D. J. Batstone*, T. Hülsen***

* Advanced Water Management Centre, The University of Queensland, Brisbane, QLD 4072, Australia (d.batstone@awmc.uq.edu.au; t.huelsen@awmc.uq.edu.au)
** CRETUS, Department of Chemical Engineering, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain (E-mail: gabriel.capson.tojo@usc.es; tel.: 0034606231495)

Abstract: Purple phototrophic bacteria (PPB) have a great potential for resource recovery from wastewater thanks to their photoheterotrophic capabilities. This work puts together available information on PPB biochemical fundamentals and the latest results from pilot-scale PPB cultivation, aiming to point research towards realising PPB full-scale implementation, with a focus on reactor design. PPB have two main requirements for an efficient phototrophic growth in enriched cultures: (i) a sufficient supply of near-infrared light and (ii) anaerobic conditions. Recent results show that effective light penetration in PPB cultures does not exceed 5-10 cm, implying that PPB open ponds (OPs) will be shallow (increasing O_2 diffusion), and photobioreactors (PBRs) will be thin (increasing capital costs). Results suggests that PPB OPs operation might be more challenging than for algae, tipping the balance towards the application of PBRs. Cost analyses must be performed using reliable data.

Keywords: anoxygenic photosynthesis; biological wastewater treatment; carbon and nutrient recovery

INTRODUCTION

Purple phototrophic bacteria (PPB) are receiving increasing attention as mediators for resource recovery from wastewaters. PPB can use light as energy source and organics as C and electron donor, via photoheterotrophic growth. This allows the simultaneous recovery of COD and nutrients as value-added products contained within the biomass (*e.g.* single-cell protein), obtained at high yields (Capson-Tojo et al., 2021b).

The main limitation for the implementation of phototrophic processes is their higher costs compared to traditional waste treatment approaches (Acién Fernández et al., 2019). If PPB processes are to become a reality, profits must be maximised, and costs must be minimised. Profit maximisation entails and optimal treatment performance and product value. Regarding cost minimisation, enriched PPB cultures must be used to avoid sterilisation costs, and sunlight must be the energy source, as artificial light sources are prohibitive. An optimal reactor design is also crucial for cost minimisation and efficient operation. PPB reactors must provide cheap/efficient mixing, efficient light distribution and must allow maximal loads, minimising reactor volumes.

Decades of research have been dedicated to optimise microalgal reactor design (Posten, 2009). The two most common cultivation technologies are photobioreactors (PBRs) and open ponds (OPs). PBRs lead to improved performances and productivities, but are more expensive, making OPs the most commonly applied configuration for growing phototrophic microorganisms (IEA Bioenergy, 2017).

While previous research on microalgae can serve as starting point for PPB, conclusions cannot be directly extrapolated, as the underlying biochemical processes in algae and PPB systems are completely different. This work aims to use the current available knowledge on PPB biochemistry to point research towards realising a feasible full-scale implementation of PPB processes. We address different crucial challenges that the technology faces, such as efficient reactor design or biomass harvesting. The latest data on pilot-scale PPB cultivation using both PBRs and OPs has been used to validate our statements.

PPB REACTOR DESIGN: CONSIDERING PPB FUNDAMENTALS

Opposed to oxygenic photosynthetic by algae, PPB perform anoxygenic photosynthesis, which has two main implications: (i) PPB use mostly near-infrared (NIR) light to grow phototrophically, and (ii) anoxic/anaerobic conditions are required. NIR-light uptake implies a more significant light attenuation, due to the higher selective absorption of NIR-light by water compared to visible-light (used by algae). Moreover, PPB reactors are operated at higher biomass concentrations than algal OPs (>1.0 vs. <0.5 $g_{VS}·L^{-1}$), further amplifying light attenuation in PPB reactors (Alloul et al., 2021; Robles et al., 2020). Anaerobic conditions are required in PPB systems because oxidative conditions (resulting from the presence of O_2) inhibit the expression of most genes required for chromatophore synthesis (Gregor and Klug, 1999). This results in the suppression of photoheterotrophic growth, colour loss, and PPB outcompetition in mixed cultures in a matter of days (Capson-Tojo et al., 2021b).

The fundamental differences pointed out above have two main implications for reactor design: (i) light-path lengths (*i.e.* width for PBRs and depth for OPs) need to be shorter in PPB systems compared to algae (*e.g.* 5-10 cm *vs.* 30 cm deep OPs, see Figure 1), and (ii) O_2 diffusion must be minimised. The latter will be incredibly challenging in open systems with high surface exchange areas, such as OPs, particularly considering that shallow ponds are needed, thus increasing the surface for gas diffusion. All considered, PPB OPs operation might be much more challenging than for algae, which might favour PBR implementation (Figure 2 shows a qualitative comparison of PBRs and OPs).

LINK WITH LATEST PILOT-SCALE PPB DATA

The light-path limits shown above agree with recent data. Results from a 8 cm thick demonstration-scale flat plate PBR (of 1 m^3, the 1st in operation; recently presented by the authors (Hülsen et al., 2021)) showed that there was no effective light limitation. Recent results from OPs (100 L) reported light limitation a depths of 10-20 cm (Alloul et al., 2021). Similar results were obtained with 15 cm deep OPs (Sepúlveda-Muñoz et al., 2020). Light limitation at 15 cm deep OPs was confirmed by other studies, where much longer retention times (4-11 d) than those commonly applied were needed (García et al., 2019; López-Serna et al., 2019).

Regarding anaerobic conditions, while this was easy to achieve in the 8 cm PBR (even when open (Hülsen et al., 2021)), this was challenging for OPs. A recent study by Alloul et al. (2021) recognised this issue, observing that dissolved oxygen (DO) minimisation in 10-20 cm deep OPs by mixing only during daytime (using a common paddlewheel) increased the PPB proportions from 14 to 56%. In addition, DO was further reduced by partial O_2 stripping caused by the CO_2 sparging system used for pH control. This need to minimise DO concentrations by low mixing intensities and small surface/volume ratios (S/Vs) to reduce O_2 diffusion (opposed to the high S/V needed for efficient light supply), will be a key factor when designing PPB OPs.

CONCLUSIONS

Although more research using demonstration-scale PBRs and OPs must be done, preliminary results and fundamental differences between PPB and microalgae suggest that PPB OP operation might be more challenging than for algae. This might tip the balance towards the application of PBRs, although the development of unexpensive options will be required. Cost analysis must be performed using experimental data.

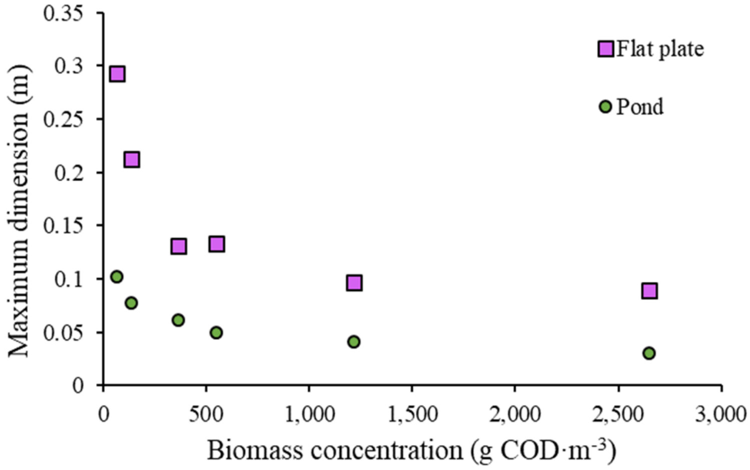
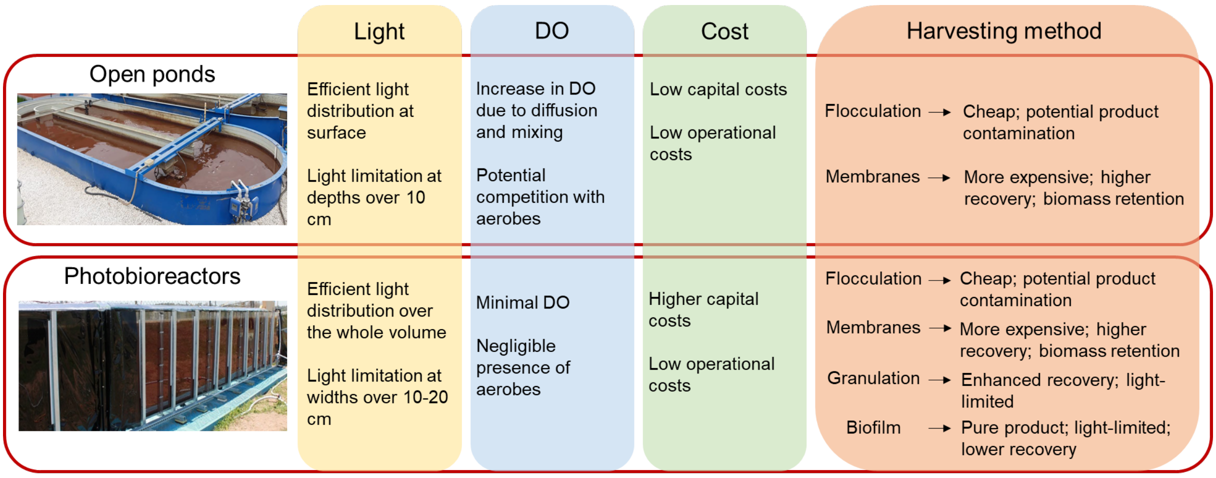


Figure 1. Maximum dimensions of different reactor configurations allowing a light intensity of 15 $W \cdot m^{-2}$ (minimum for effective phototrophic uptake rates) throughout the whole reactor volume (assuming an incident light intensity of 400 $W \cdot m^{-2}$) (extracted from recent work of the authors, see Capson-Tojo et al. (2021a)).



Pictures from: (up) Phototrophic Purple Bacteria Ponds © AQUALIA and (down) flat plate PBR from the University of Queensland

Figure 2. Qualitative comparison between open ponds and photobioreactors. Their main characteristics regarding light distribution, dissolved oxygen (DO) presence, cost, and applicable harvesting methods are given. Harvesting is not discussed in the text due to space limitations.

REFERENCES

Acién Fernández, F.G., Fernández Sevilla, J.M., Molina Grima, E., 2019. Costs analysis of microalgae production, Second Edi. ed, Biofuels from Algae. Elsevier B.V.

Alloul, A., Cerruti, M., Adamczyk, D., Weissbrodt, D.G., Vlaeminck, S. 2021. Operational Strategies to Selectively Produce Purple Bacteria for Microbial Protein in Raceway Reactors. *Environ. Sci. Technol.* **55**, 8278–8286.

Capson-Tojo, G., Batstone, D.J., Hülsen, T. 2021a. Implications of light attenuation for the upscaling of mixed purple phototrophic bacteria processes, in: *4th IWA Resource Recovery Conference*.

Capson-Tojo, G., Lin, S., Batstone, D.J., Hülsen, T. 2021b. Purple phototrophic bacteria are outcompeted by aerobic heterotrophs in the presence of oxygen. *Water Res.* **194**, 116941.

García, D., de Godos, I., Domínguez, C., Turiel, S., Bolado, S., Muñoz, R. 2019. A systematic comparison of the potential of microalgae-bacteria and purple phototrophic bacteria consortia for the treatment of piggery wastewater. *Bioresour. Technol.* **276**, 18–27.

Gregor, J., Klug, G. 1999. Regulation of bacterial photosynthesis genes by oxygen and light. *FEMS Microbiol. Lett.* **179**, 1–9.

Hülsen, T., Züger, C., Batstone, D.J., Capson-Tojo, G. 2021. Practical implementation of a modular and scalable 1 m3 outdoors flat plate photobioreactor for resource recovery with purple phototrophic bacteria, in: *4th IWA Resource Recovery Conference*.

IEA Bioenergy, 2017. *State of Technology Review – Algae Bioenergy*.

López-Serna, R., García, D., Bolado, S., Jiménez, J.J., Lai, F.Y., Golovko, O., Gago-Ferrero, P., Ahrens, L., Wiberg, K., Muñoz, R. 2019. Photobioreactors based on microalgae-bacteria and purple phototrophic bacteria consortia: A promising technology to reduce the load of veterinary drugs from piggery wastewater. *Sci. Total Environ.* **692**, 259-266.

Posten, C. 2009. Design principles of photo-bioreactors for cultivation of microalgae. *Eng. Life Sci.* **9**, 165-177.

Robles, Á., Capson-Tojo, G., Gales, A., Viruela, A., Sialve, B., Seco, A., Steyer, J.-P., Ferrer, J. 2020. Performance of a membrane-coupled high-rate algal pond for urban wastewater treatment at demonstration scale. *Bioresour. Technol.* **301**, 122672.

Sepúlveda-Muñoz, C.A., Ángeles, R., de Godos, I., Muñoz, R. 2020. Comparative evaluation of continuous piggery wastewater treatment in open and closed purple phototrophic bacteria-based photobioreactors. *J. Water Process Eng.* **38**, 101608.