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Note to Editor: Microalgae cultivation for wastewater treatment and biofuel production: a bibliographic overview of past and current trends

Rigorous interest in the quality of surface waters and the related field of treatment of municipal and industrial wastewaters is not novel. Standards to protect environmental quality were developed by the UK Royal Commission on Sewerage Disposal in 1898 [1]. However related research activities become more obvious in the peer-reviewed publication record after the late 1960's [2,3] reflecting the industrial and urban expansion of the times and the increasing awareness of the impact on surface water. This created the impetus for regulatory authorities to introduce environmental controls on water quality and on urban and industrial emissions. The creation by US EPA of the Clean Water Act of 1972, designed to regulate the restoration and to uphold the quality of the water sources in the United States, is such an example. Related regulations on water discharge stimulated investigations on effective means of nutrient removal, primarily N and P, including the option of microalgae, to mitigate eutrophication of surface waters [2]. Nevertheless, the use of algae to treat wastewaters for reduction of nutrients and biological oxygen demand (BOD) has long been considered as an effective alternative to conventional biological wastewater treatment processes, to achieve environmental quality standards [2,4]. Significant peer reviewed literature targeting the use of [micro]algae as an option for wastewater treatment can be traced to about 1977, and, although mentioned before [5], the first clear statement on the value of wastewater for algal production appeared in 1979 [6]. Subsequently, US national programs aimed at developing algal based biofuels also integrated wastewater research elements, a trend especially evident after 1980 [7,8]. Other bio-products, such as ethanol from residual starches, residual protein for animal feed, nutraceuticals, or even bioplastics may be also be obtained from algal residues left behind after the extraction of lipids for biofuel [8]. The significant nutrient demand of large-scale algae biomass production also provided the opportunity to couple the treatment of high nutrient content wastewaters with algal growth [6,7]. An additional benefit of wastewater treatment with algae is the capacity to fix CO_2 [9–12]. Biological nutrient removal from wastewater by a range of algal species is effective in a variety of engineered systems including traditional ponds, high rate algal ponds (HRAP [13]). By combining wastewater treatment with algal biofuel production, biological wastewater treatment processes, which are usually a significant energy sink, can be converted into a positive energy source [8,14].

Therefore, in recent years, research has been devoted to enhancing efficiency of the process of creating biofuels from wastewater derived algal biomass. While other valuable bio-products can and are also obtained from wastewater cultured algae, often from the same harvest [8], the principal driver of our review is the production of biofuels. Literature reviews regularly published on the subject are often written as expert opinions, an approach intrinsically selective. Here we assessed the current state of the science as published, by analysing keyword datasets descriptive of peer-reviewed publications as summarised by a publicly available curated database. By not relying on an expert opinion approach, we did not select results based on their perceived quality; articles were retained if they met the respective search criteria, and thus their contribution to the keyword dataset was not-biased by a quality judgment. We then examined apparent historical trends in research on the application of algae in wastewater treatment to possibly identify critical research priority areas. Methodological details can be found in the Supplementary data.

1. Variation in publications counts

The annualized rate of increase in publication counts can be used to reveal the maturity of a research field. A mature research area, such as “water” or “algal research”, while producing many publications, has a small proportional rate of increase in publication counts from year to year. Interestingly, the broad topic of using algae for wastewater treatment in general, follows the behaviour of a relatively mature field despite the comparatively smaller publication count (Fig. 1a). On the other hand, the large annualized increase rates in manuscript counts for algae for biofuel production, with or without wastewater, suggest a new and expanding field. This is confirmed by the similar trend observed in publication rate for wastewater/algae (wwt/a) and wastewater/algae/biofuels (wwt/a/bf), with the latter a 20% subset of wwt/a (Fig. 1b). This trend was consistent irrespective of the type of wastewater type considered (municipal, industrial, and farm wastewater streams) for either treatment or biofuel production.

2. Keyword utilization patterns

The variation in keyword usage intensity conjectures the rationale and context of the associated research area. The analysis confirms that early interest in wastewater treatment was driven primarily by environmental concerns (Fig. 2) with less focus on utilization of wastewaters for resource recovery as substrates in bioreactor or like systems. Thus, environmental impact keywords were identified in about 50% of the 1972–1973 related publications (Fig. 2). This was followed by a sustained increase in modelling efforts, likely summarizing the extensive modelling of wastewater

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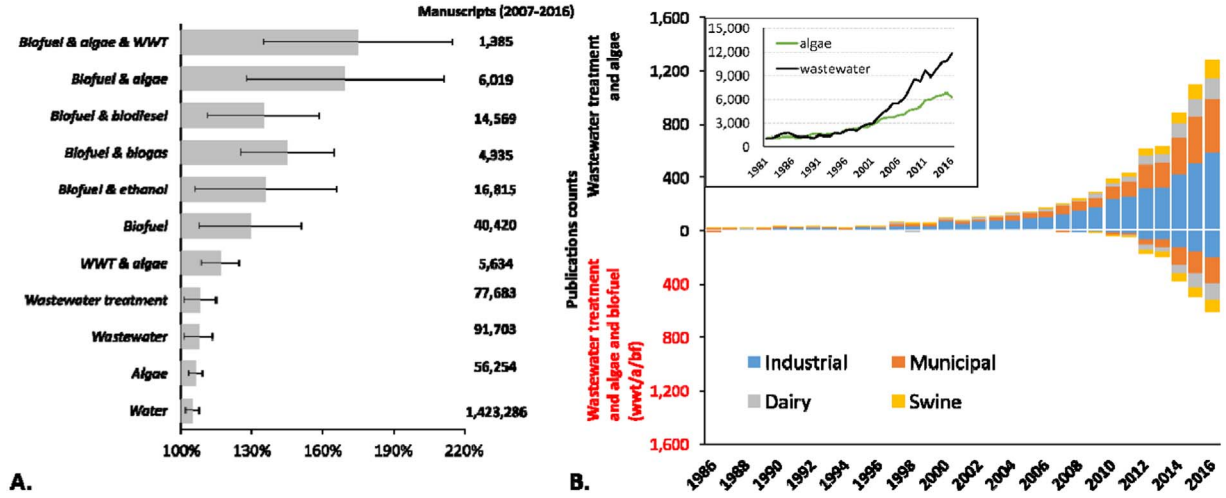

Fig. 1. Publications for selected research areas (SCOPUS search results obtained on January 18, 2017); error bars are 95% Confidence Intervals); Manuscript counts sum the period from 2007 through 2016. A. Publications; average annual increase rate and total (2007–2016); B. Publications related to algae and biofuels across wastewater types.

treatment carried out by the profession of Civil Engineering [3]. It is interesting to also note the sustained and simultaneous increase of environmental impact and modelling research in the 1990–2000 period (Fig. 2).

Wastewater treatment aims to lower BOD and remove nutrients to minimize eutrophication risks [4]. It is noteworthy that the pollution focus of the wwt/a publications is also associated with a significantly stronger focus on metal and toxicity terminology (see Supplementary data, Table 6); average abundance for the keywords subsets including As, Cd, Cr, Cu, Ni, Zn, "metals" and "metal ions" was 1.36% ± 0.69% for wastewater (wwt) and 4.39 ± 1.66% for wwt/a; none were found in the wwt/a/bf publications dataset. This strengthens the notion that addition of algae to the wastewater treatment technologies was initially done with the goal of treatment and not for obtaining algal bio-products.

After 2000 "modelling" dominates the wwt publications (11.5%), "management" and "water pollutants/pollution" are comparably represented in the wwt/a publications (20.1% and 19.0%, respectively), and "biomass", at 72.8%, clearly dominates the ww/a/bf publications. Nevertheless, research on modelling of wastewater systems, while relatively constant from 1970 through early 2000's, declined in the last 10 years. This underlying trend, that occurred while publication in the www/a/bf research area accelerated, is a significant concern. It suggests that much of the recent research is exploratory in scope and likely narrative in nature. Therefore, the development of coherent management tools for algal wastewater treatment processes might be justifiably considered as a priority area for future research investment;

Where wastewaters are primarily employed for algal growth and biomass production the availability of nutrients becomes a critical aspect of the treatment system. More recently "nutrients" and "nutrient removal", in the context of algal biofuel, have received greater attention by the international research community, and, concomitantly, bioreactor based research has also expanded; the increased intensity of keywords describing bioreactor type (Fig. 2a) towards 1996 coincides with the conclusion of the first concerted effort to evaluate the utility of algae for energy production [7]. The intensity of research on nitrogen and phosphorus, in general, follows a similar trend; research on nutrient removal reached its maximum intensity in 2010, coinciding with a significant output of wwt/a/bf research (Fig. 2) in the middle of the current surge in wastewater and algae for biofuel research [8]. A closer look at keyword abundance after 2000 shows that while "nutrient removal" dominates (28.1% for wwt/a, and 17.5% for wwt/a/b), "nutrient availability" or "uptake" received very little attention (0.97% and 0.78%, for wwt/a and respectively wwt/a/bf, and not present in the wwt dataset; Supplementary data, Table 6). This confirms that, whilst nutrient removal, i.e. wastewater treatment, was the key focus of research, the interest in use of wastewater as a nutrient source was only establishing. The increasing use of "nutrient" for the wwt/a/bf literature

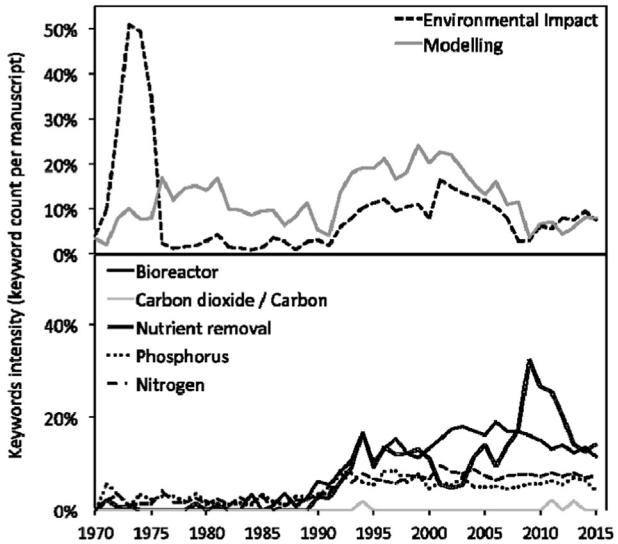

Fig. 2. Utilization rates for selected keywords for the "wastewater treatment" query (SCOPUS search results obtained on May 18, 2016).