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Oil and gas produced water as a growth medium for microalgae cultivation: A review and feasibility analysis

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ABSTRACT

Scale-up of microalgal biotechnology to provide large quantities of biofuel, lipids, and coproducts is not fully developed because of the large needs for nutrients, water, land, solar insolation, and CO_2/carbon supplies. Wastewaters, including oil and gas produced water (PW), may supply a portion of these needs in regions with insufficient fresh water resources. PW is a challenging water resource for this use because of variable salinity, geochemical complexity, and the presence of biologically toxic components. In this paper we review PW volumes, quality, and use in media for microalgae production in the southwestern US, Australia, and Oman. We also include data from the southwestern US, referencing previously unpublished results from the National Alliance for Biofuels and Bioproducts (NAABB) consortium research project. We include a Supplementary Information section that explores cultivation of multiple microalgae species in PW and examines the carbon utilization process, all work performed in support of the NAABB field program.

Strains of algae tested in the reviewed papers include *Nannochloropsis*, *Dunalliella*, *Scenedesmus*, and several mixed or unknown cultures. We conclude that the use of PW in algae cultivation is feasible, if the additional complexity of the water resource is accounted for in developing media formulations and in understanding metals uptake by the algae. We recommend additional work to standardize growth testing in PW, better and more thorough chemical analysis, and geochemical modeling of the PW used in media. Expanded strain testing in PW media will identify improved strains tolerant of PW in algae cultivation.

1. Introduction

Scale-up of algal biotechnology to provide large quantities of biofuel, lipids, and coproducts remains challenging because of the large needs for nutrients, water, land, solar insolation, and CO_2/carbon supplies [1]. Wastewaters, including oil and gas produced water (PW), may supply a portion of these needs in regions with insufficient fresh water resources [2–4]. PW co-extracted with oil and gas has great potential economic value for algal biofuel production, and could reduce fresh water limitations to creating a viable algal biofuel industry [2,5–7]. Use of PW in place of fresh water allows conservation of fresh water for high-value uses such as food production, particularly in arid regions where fresh water resources are scarce. However, there is little information available regarding the availability, quality, toxicity, and overall feasibility of PW for cultivation use, either in the United States or internationally.

Water consumption of 20 million megaliters (ML) is estimated to be needed to supply a 75,000 ML algae oil production scenario in the southwestern US [2], while more water will be needed for processing and fuel conversion [6,8–10]. This level of consumption would put a considerable strain on fresh water resources in arid regions. PW is a potential brackish or saline replacement for fresh water resources in biofuel algae growth media for such lipid production strains as *Nannochloropsis*. Fresh water species such as *Scenedesmus* and *Tetracystis* also can be adapted to brackish PW. Brackish and saline algae growth media limits competition with fresh water otherwise allocated to agriculture, community use, or energy production

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sectors. PW quality data are needed to determine if the wastewater can be used successfully for biofuel algae media.

PW volume and location data are needed in order to evaluate where algae cultivation could be co-located. Oil and gas production in the United States currently brings 3 million ML of PW to the surface annually [11]. In Australia, coal bed methane (CBM) production, also known as coal seam gas (CSG), has an associated water production of 20–40 m^3/day (7.3–14.6 ML/year) in Queensland alone. In total, Australia produced an estimated 33 GL in 2010 (3300 ML/year) including Queensland, New South Wales, and South Australia; growing to over 300 GL/year in the future [12–14]. In Oman, crude oil production in the al-Wusta region results in 800,000 m^3/day (292 ML/year) of PW [15]. In the United States, most (~80%) PW is later reinjected, either for disposal purposes or for enhanced oil recovery. However, problems with disposal have been widely documented, including the occurrence of disposal-related earthquakes and potential ground water contamination [16–19]. Finding new opportunities to reuse PW instead of disposal is of interest in the U.S. In Australia, several potential management options for CSG PW, including reinjection, treatment for use in municipal supplies, agriculture, and industrial use have been explored [14]. In Oman, deep well injection, injection for pressure maintenance, and shallow reinjection are used for disposal [20,21]. Wetlands projects for brackish PW use and salt recovery have been documented [22]. This treatment, along with algae cultivation, is being explored in order to phase out shallow PW reinjection for disposal. All of these regions are arid in nature with severe shortages of fresh water. Utilizing PW through microalgae cultivation based on available land and solar insolation resources provide alternative disposal options [23–26].

Salinity of PW worldwide varies from near fresh (<1000 ppm TDS) to highly saline (>200.000 ppm TDS) depending upon the source formation and region [27]. Salinities near seawater concentrations or lower, are the best for algae growth. Additionally, PW is typically contaminated with organic compounds derived from reservoir hydrocarbons, trace metals, and chemical additives (surfactants, KCl, methanol, biocides) used to enhance oil and gas production. These compounds may be toxic to the algae.

While disposal of PW is closely regulated in the United States, international disposal regulations vary widely. Disposal of PW is always an added complication and expense for oil and gas operations. Use of this water for any purpose has been regarded as problematic worldwide because of the large volumes, disposal costs, and the potential for environmental contamination. Algae cultivation for biofuels and other products provides an alternative use for this wastewater.

Recent interest in using wastewater resources such as PW for economic algal biofuel production has inspired a number of questions regarding the feasibility of PW use, as follows:

1. Is PW available as a substitute for fresh water in regions where algae can be cultivated?
2. Is the quality (predominantly, salinity) of the water acceptable for algae cultivation? What advantages or disadvantages might PW bring to cultivation media in terms of native chemical composition?
3. Does PW contain chemical constituents that may be toxic to algae?
4. Does PW contain constituents that may be adsorbed by algae or otherwise transmitted to consumers of algae coproducts, including animals, fish, and humans?
5. Will reasonable dilution rates using PW be feasible to maintain optimal salinity in open ponds in arid regions with high evaporation rates?
6. What treatment methods might be needed in order to make the water useable for algal cultivation?

The aims of this paper are to provide 1) an international literature review of examples of PW use for algae growth, and 2) to present additional U.S. data collected during the National Alliance for Biofuels and Bioproducts (NAABB) program on oil and gas PW for algae cultivation ([28] and Supplementary Information). We introduce the concept of PW as a media substrate, the potential availability of PW for algal biofuel production in the arid regions of the United States, Australia, and Oman, and review recent information from sampling of PW sources in the southwestern United States (New Mexico, Texas, and Colorado) as a test case example. The three locations reviewed here exemplify regions where it is feasible to locate algal production facilities adjacent to PW sources. Sufficient volumes of PW can then be accessed for extended periods of time providing an alternate source of water that is economically and practically feasible. The locations are good examples of places where research in PW uses and algal production intersect. This paper describes some effects of PW source quality, evaporation, treatment, and media mix creation on PW media quality. We intend for this to provide a framework for future research into the potential of PW for algal biofuel production, and as a methodology resource for evaluation and use of PW for this purpose.

2. Literature review

2.1. Produced water availability-locations and volumes of PW in the study regions of the southwestern United States, Australia, and Oman

PW availability is a combination of location, volume, transportation, and economic factors that create a favorable environment for PW use versus other, less chemically complex water sources.

Veil [29] reports the most recent comprehensive data (2012) for PW volumes by state for the US. The US as a whole extracted 3,367,453 ML of PW along with oil and gas in 2012. This was only a 1% increase in volume over 2007 levels, despite a 22% increase in oil and gas production during this time indicating that PW supplies are likely to be stable. Colorado and New Mexico combined extracted 180,342 ML, while Texas extracted 1,182,175 ML.

New Mexico produced 84,943 ML of water from oil production in 2007 (a 10:1 water:oil ratio), increasing to 107,301 ML in 2012 (8:1 ratio). The state also produced 18,834 ML in 2007 from conventional gas and coal bed methane (CBM) gas production combined [11] [29]. Slightly less gas PW was extracted in 2012 (16,062 ML) resulting from decreased gas production trends. The region where fresh water shortages and hydrocarbon production most frequently overlap is in the Permian Basin in southeastern NM (Eddy, Chavez, and Lea counties) and west Texas [30]. The Four Corners region (northwestern New Mexico including San Juan and Rio Arriba counties, and southwestern Colorado) also has abundant supplies of coal-bed methane and oil-PW. This region features rugged topography and cooler climate conditions, factors that are less favorable to algae production [23].

As a whole, New Mexico fresh water supplies are nearly fully allocated via a water rights system [31]. Acquisition of water rights for any industrial or agricultural purpose can be expensive and is dependent upon a limited sales market [32]. Colorado has a similar water rights system and is heavily allocated to current users [33]. West Texas utilizes a "right of capture" water allocation system for ground water that encourages pumping by land owners [34]. Texas, New Mexico, Colorado, and the southwestern US have experienced severe drought-related water shortages in recent years. There is active review and exploration of alternative brackish and saline water resources to replace fresh water in this region (e.g., Sabie et al. [35]). Recent analysis of the boom in hydraulic fracturing in the United States, a process that uses large quantities of water [36,37], shows that the demand for water for these activities, particularly in the western United States, has increased dramatically and is exacerbating water stress. PW is not "righted" water and is managed outside of the water rights system making it more available than fresh water in oil and gas production areas. Regardless of drought, fresh water for large-scale algae cultivation in the southwestern US region will remain in competition with existing water users including irrigators, municipalities, and industry.

Hamawand et al. reviewed the production of CBM PW, also known as coal-seam-gas (CSG) PW in Australia [38]. Australia produces a