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National Algal Biofuels Technology Roadmap

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A technology roadmap resulting from the National Algal Biofuels Workshop
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John Ferrell
Office of Energy Efficiency
and Renewable Energy
Office of the Biomass Program
(202)586-5340
john.ferrell@ee.doe.gov

Valerie Sarisky-Reed
Office of Energy Efficiency
and Renewable Energy
Office of the Biomass Program
(202)586-5340
valerie.sarisky-reed@ee.doe.gov

Roadmap Editors:
Daniel Fishman,[1] Rajita Majumdar,[1] Joanne Morello,[2] Ron Pate,[3] and Joyce Yang[2]

Workshop Organizers:
Al Darzins,[4] Grant Heffelfinger,[3] Ron Pate,[3] Leslie Pezzullo,[2] Phil Pienkos,[4] Kathy Roach,[5] Valerie Sarisky-Reed,[2] and the Oak Ridge Institute for Science and Education (ORISE)

A complete list of workshop participants and roadmap contributors is available in the appendix.

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[1]BCS, Incorporated [2]Office of the Biomass Program [3]Sandia National Laboratories

[4]National Renewable Energy Laboratory [5]MurphyTate LLC

not be seen as suitable for algae production. The same applies to land highly suited for higher-value agricultural use. Beyond economics, this also avoids the perception and potential conflict of food and feed production versus fuel. Sensitive environmental or cultural land constraints will also reduce the overall land availability (Maxwell et al., 1985). Examples of this type of constraint include parks, monuments, wildlife areas, archaeological sites, and other historical sites. On the other hand, some land cover characteristics could present excellent opportunities for algae farming. Land cover categories such as barren and scrubland cover a large portion of the West and may provide an area free from other food-based agriculture where algae growth systems could be sited (Maxwell et al., 1985). The availability and sustainability of water supplies in the West will also be a key consideration, as noted earlier.

9.4 Integration with Water Treatment Facilities

Inevitably, wastewater treatment and recycling must be incorporated with algae biofuel production. The main connections of algae production and wastewater treatment are the following:

- Treatment technology is needed to recycle nutrients and water from algae biofuel processing residuals for use in algae production.
- Imported wastewater provides nutrients and water to make-up inevitable losses. The imported wastewater would be treated as part of the algae production.
- Algae-based wastewater treatment provides a needed service.
- Algae-based wastewater treatment can be deployed in the near-term and provides workforce training and experience in large-scale algae cultivation that would translate to future dedicated algae feedstock production facilities.

For large-scale algae biofuel production, nutrients from wastewater (municipal and agricultural) would be captured by algae and then recycled from the oil extraction residuals for additional rounds of algae production. Nutrient recycling would be needed since wastewater flows in the United States are insufficient to support large-scale algae production on the basis of a single use of nutrients. Inevitable nutrients losses during algae production and processing could be made up with wastewater nutrients, which can also help supplement and off-set the cost of commercial fertilizers for algae production. Supply and cost of nutrients (nitrogen, phosphorus, and potassium) be a key issue for achieving affordable and sustainable scale-up of algae biofuels production.

POTENTIAL BENEFITS OF ALGAE PRODUCTION WITH WASTEWATER TREATMENT

Although algae-based wastewater treatment requires many times more land area than mechanical treatment technologies, in suitable climates, algae-based treatment has the following advantages:

- Early opportunity to develop large-scale algae production infrastructure
- Development of skilled algae production workforce
- Potential for nutrient recycling at algae biomass production facilities
- Wastewater treatment revenue that offsets algae production costs
- Lower capital and O&M costs than conventional wastewater treatment
- Lower energy intensity than conventional wastewater treatment (a greenhouse gas benefit)
- Potential to be integrated with power plant or other CO_2-emitting industry operations
- Potential to treat agricultural drainage and eutrophic water bodies

Wastewater Treatment and Recycling Applications

Municipal wastewater treatment facilities and agricultural dairy and feedlot operations located throughout the United States, particularly in the eastern half of the country, represent potential co-location sites for algae operations where nutrient-rich wastewater could be used for algae production, and the algae production can help provide nutrient removal service in the wastewater treatment. Two main types of algae production facility are envisioned: dedicated facilities, with the main purpose of biomass production, and wastewater treatment facilities, which produce algal biomass as a consequence of the wastewater treatment. Dedicated biomass production facilities will also require wastewater treatment and nutrient recycling. A subset of wastewater treatment facilities consist of evaporation facilities, which are used to dispose of wastewater or brines. The roles of these facility types in the development of an algae biofuels industry are discussed in this subsection.

Algae can be useful in the treatment of waters polluted with organic matter, excess nutrients (e.g., nitrogen, phosphorus, and potassium), metals, synthetic organic compounds, and potentially endocrine disrupting compounds (Oswald, 1988; Woertz et al., 2009; Aksu, 1998; Borde et al., 2002). High rates of algae production lead to high rates of nutrient removal and wastewater treatment. Thus, the objectives of biofuel feedstock production and wastewater treatment are aligned, at least in terms of maximizing biomass production. Maintenance of lipid-rich strains, or manipulation of culture conditions to promote lipid production, have yet to be demonstrated consistently for ponds, including wastewater treatment ponds.

Algae-based treatment facilities are typically less expensive to build and to operate than conventional mechanical treatment facilities. For example, high-productivity algae ponds have a total cost that is about 70% less than activated sludge, which is the leading water treatment technology used in the United States (Downing et al., 2002). This cost savings, coupled with the tremendous need for expanded and improved wastewater treatment in the United States (EPA, 2008) and throughout the world, provides a practical opportunity to install algae production facilities in conjunction with wastewater treatment. The major classes of wastewaters to be treated are municipal, organic industrial (e.g., food processing), organic agricultural (e.g., confined animal facilities), and eutrophic waters with low organic content but high nutrient content (e.g., agricultural drainage, lakes, and rivers). Despite a seeming abundance of wastewater and waste nutrients, recycling of nutrients and carbon at algae production facilities will be needed if algae are to make a substantial contribution to national biofuel production. Even with internal recycling, importation of wastes and/or wastewater will still be needed in dedicated algae biomass production facilities to make up for nutrient losses (Brune et al., 2009).

Algae Production Techniques for Wastewater Treatment Plants

Integration of algae production with wastewater treatment is illustrated schematically in Exhibit 9.7. Existing algae-based treatment facilities use relatively deep ponds (1-6 m). The great depths contribute to low algae productivity, but high productivity is not crucial to the treatment goals of these facilities (removal of organic matter and pathogens only). Ponds for more advanced treatment, including nutrient removal, need high algae productivities (as does biofuels feedstock production). These highly productive systems use shallow reactors, either high rate ponds (~30 cm) or algal turf scrubbers (~1 cm). Closed photobioreactors are not emphasized in this wastewater treatment discussion since they are likely to be economical only when also producing high-value products (>$100/kg biomass), which is unlikely when wastewater contaminants are present.

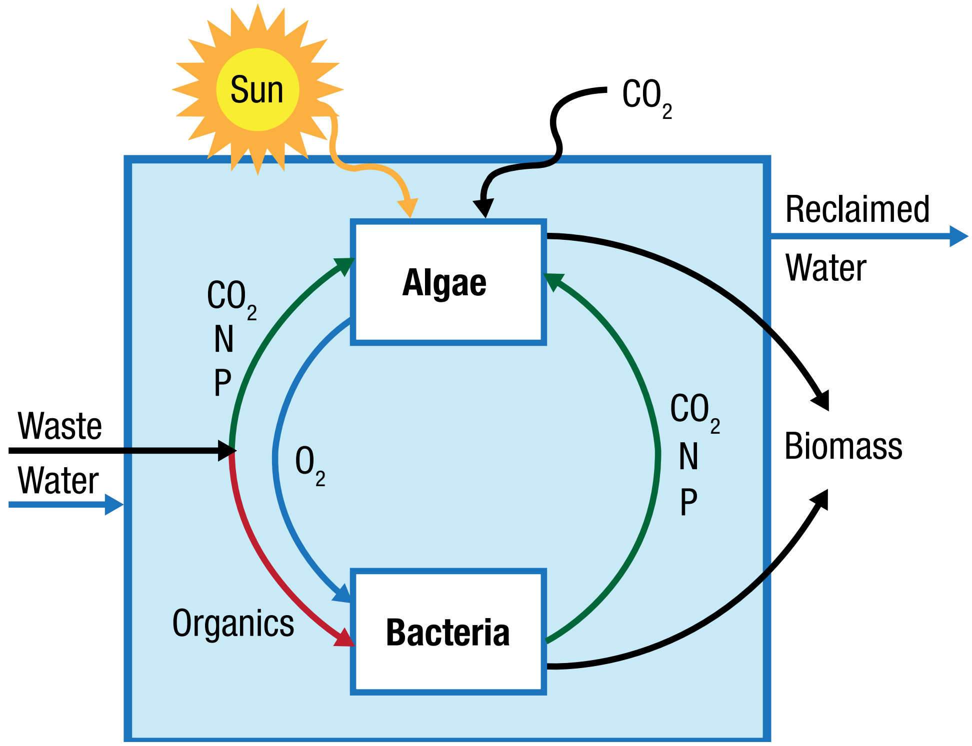
As with other algae production systems, harvesting is a crucial step in wastewater treatment systems. The standard method is chemical addition to achieve coagulation and flocculation, followed by algae separation in dissolved air flotation units or sedimentation clarifiers. The cost of chemical addition ($0.10 - $0.17 per m3 treated) (Maglion, 2008) is high for biofuel production. Non-chemical flocculation processes (bioflocculation and autoflocculation) are far less costly, but research is needed to improve the reliability of these processes (as discussed in chapter 4). As noted above, the major types of wastewaters available for combined algae production and water treatment are those contaminated with organic matter and nutrients (e.g., municipal and industrial sources) and wastewaters mainly contaminated with inorganic nutrients (e.g., agricultural drainage, rivers, and lakes).

Treatment of Organic Wastewaters for Algae Production

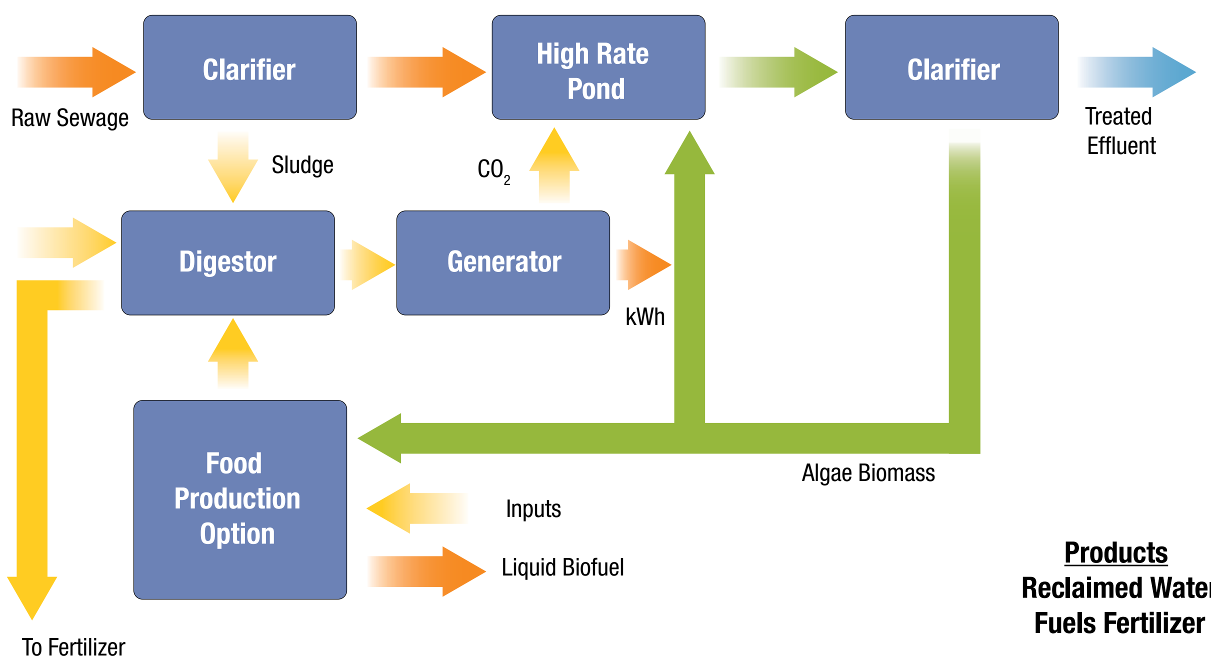
Organic-rich wastewaters usually also contain nutrients, requiring two types of treatment. Algae are similar to plants in that they both produce oxygen and assimilate nutrients. These reactions are also the best-known mechanisms of wastewater treatment by algae. The dissolved oxygen algae release is used by treatment bacteria to oxidize waste organic matter (Exhibit 9.7). The ability of algae to assimilate dissolved nutrients down to trace concentrations is useful in wastewater treatment, if the nutrient-rich algae are then also removed from the water. Less well-known are the ability of algal systems to provide natural disinfection and remove trace contaminants. Disinfection is promoted via the production of oxygen radicals in the presence of sunlight, dissolved oxygen, and naturally occurring organic catalysts (Sinton et al., 2002, Kohn et al., 2007). Heavy metals may be removed by adsorption to algal cells, which will be a benefit as long as the resulting metals concentrations in the algae biomass are not excessive or inhibitive for later use in the processing of fuel and other co-products. Finally, the interaction of algae and bacteria in wastewater cultures leads to degradation of a wide variety of synthetic organic compounds such as phenol and acetonitrile (Borde et al., 2003, Muñoz et al., 2005). The removal of trace contaminants (e.g., endocrine disrupting compounds such as human hormones and antibiotics from animal facilities) is an area in need of study.

Mechanical treatment technologies typically hold the wastewater for less than 12 hours, whereas pond technologies hold the wastewater for at least several days and in an environment similar to many natural receiving waters. The bioaccumulation of trace contaminants in algae that would occur in the receiving waters, eventually harming higher organisms, might be prevented to a

Exhibit 9.7 *Integration of algae production with wastewater treatment for nutrient removal and biomass production:*



a) *Basic principles of operation;*



b) *Simplified conceptual system block diagram* great extend by pond treatment followed by algae harvesting. The processing of the algal biomass for fuel and other co-products would presumably destroy and neutralize the contaminants, but further investigation is needed to confirm this. However, any heavy metals contaminating the algal biomass likely would remain in the waste from biofuel processing, potentially increasing the cost of waste disposal or recycling. For all biofuel feedstocks, routes of such contamination should be studied and preventative measures developed.

Treatment of Inorganic Wastewaters for Algae Production

In addition to the ability of algae systems to treat organic-rich wastewaters, their ability to treat high-nutrient, low-organic content wastewaters will expand the opportunities for algae production systems. Agricultural drainage and eutrophic water bodies (e.g., Salton Sea, Calif.) are examples of such waters (Benemann et al., 2002). Treatment of nutrient-rich waters is likely to occur in more rural settings than treatment of municipal wastewaters, potentially leading to greater land availability and savings in land costs.

For algae-based treatment of low-organic content wastewaters, CO_2 addition or slow atmospheric absorption is essential since inorganic carbon generation from decomposition of organic matter would not be significant. Treatment of agricultural drainage with algal turf scrubbers without CO_2-addition and high rate ponds with CO_2 addition has been demonstrated in California's Central Valley and elsewhere (Craggs et al., 1996; Mulbry et al., 2008; Lundquist et al., 2004).

High rate ponds might be used as components of evaporation systems needed to dispose of blow-down or other wastewater. The high rate ponds could create an algal product while performing the service of water evaporation. Evaporation ponds are currently used to dispose of agricultural drainage, oil field produced water, mine drainage, etc. As with any evaporation pond system, hazards to wildlife from toxic compounds (e.g., selenium, chromium) must be carefully evaluated.

Main Research Needs for Algae Production with Wastewater

Successful use of high rate ponds specifically for nutrient removal/recycling requires resolution of several issues, as follows:

- Large-scale (3-5 acre) demonstration of CO_2-enhanced high rate ponds for nutrient removal
- Determine CO_2 biofixation efficiency
- Determine growth model parameters
- Develop algae grazer control strategies
- Develop reliable low-cost algae harvesting techniques, such as bioflocculation, autoflocculation, micro-screening, etc.
- Demonstrate recycling of biofuel processing wastes for algae production
- Determine the cost savings and greenhouse gas (GHG) emissions avoidance benefits compared to conventional wastewater treatment technologies.

9.5 Co-location of Algal Cultivation Facilities with CO_2-Emitting Industries

This section includes findings from discussions held at the National Algal Roadmap Workshop break-out sessions, and additional input sought from managers at major electric utilities through later meetings and conference calls. These follow-on efforts were coordinated with the Electric Power Research Institute (EPRI), and included several large municipal electric utilities. The topics of discussion included the value proposition, desired outcomes, integration opportunities and challenges, market drivers, technical and market challenges, constraints on large-scale development, co-products, and potential opportunities for the federal government. Findings from these interviews and conference calls were integrated with the Workshop inputs in developing this section. It is important to point out that amongst the numerous barriers to co-location of algal cultivation facilities with industrial CO_2 sources identified at the Workshop and subsequent discussions with electric utilities, an overriding theme was that electric utilities primarily view algae cultivation as a means of CO_2 capture as opposed to a method for producing biofuels and co-products. Thus, electric utilities may need to partner with algae cultivation/technology companies and fuel refiners/distributers with very different business models and goals for algae production in order for this type of co-location to be widely commercialized. Furthermore, research efforts and policy evaluations would likely need to focus on both carbon capture and the production of biofuels and co-products to overcome barriers (technical, regulatory and economic) for algae facilities that are co-located with electric utilities and other industrial CO_2 sources.