ERDC/EL TR-23-10

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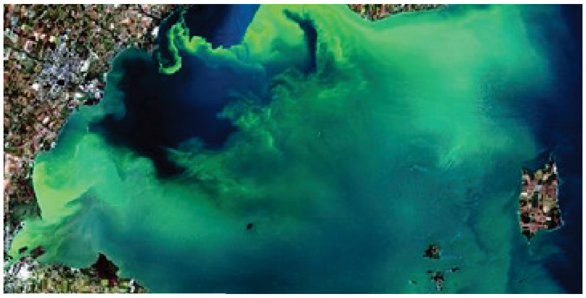
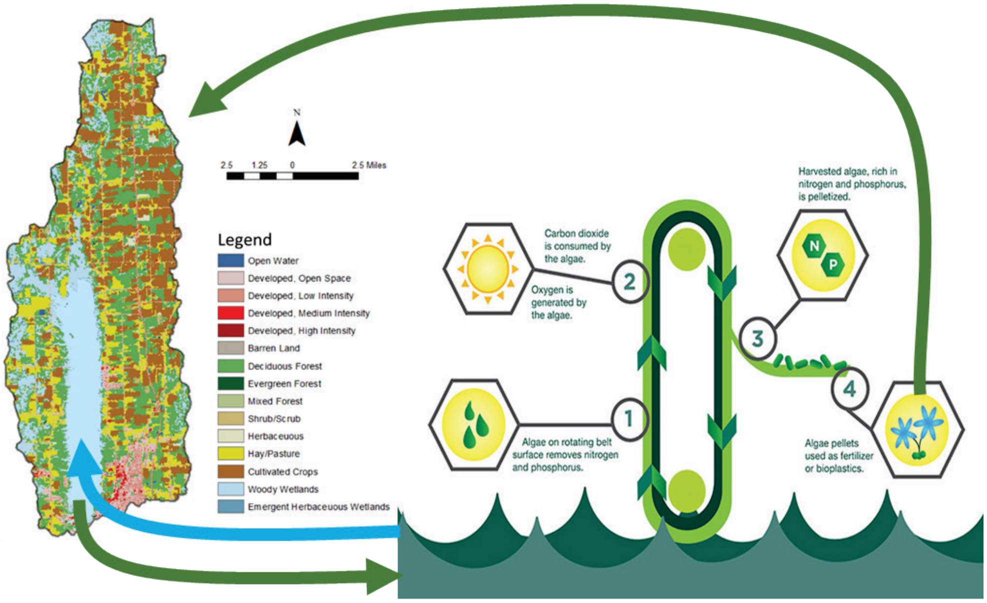
Aquatic Nuisance Species Research Program

A Review of Algal Phytoremediation Potential to Sequester Nutrients from Eutrophic Surface Water

Chuck Theiling

September 2023





Environmental Laboratory

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Under Aquatic Nuisance Species Research Program (ANSRP) Harmful Algal Bloom Congressional Interest project entitled “Algal Phytoremediation for Nutrient Reduction”
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Abstract

Harmful algal blooms (HABs) and coastal hypoxic zones are evidence of cultural nutrient enrichment affecting public health and water supplies, aquatic ecosystem health, and economic well-being in the United States. Recognition of the far-reaching impacts of Midwest agriculture has led to establishing nutrient reduction objectives for surface waters feeding the Gulf of Mexico, Lake Erie, and many smaller water bodies. Municipal nutrient enrichment impacts have been addressed by increasing levels of sewage treatment and waste management through the Clean Water Act era, but HABs rebounded in the 1990s because of non-point source nutrient enrichment. HAB control and treatment includes watershed and waterbody treatments to reduce loading and address outbreaks. Systems to remove nutrients from impaired waters are expensive to build and operate. This review of algal production systems summarizes emerging algal water treatment technologies and considers their potential to effectively sequester nutrients and atmospheric carbon from hundreds of eutrophic reservoirs and DoD wastewater treatment facilities while producing useful biomass feedstock using solar energy. Algal water treatment systems including open ponds, photobioreactors, and algal turf scrubbers® can be used to grow biomass for biofuel, wastewater treatment, and commercial products. This review recommends continuing research on surface water nutrient reduction potential with algal turf scrubber productivity pilot studies, preliminary site design, and biomass utilization investigations.

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Preface

This study was conducted for the Aquatic Nuisance Research Program under Project “Algal Phytoremediation for Nutrient Reduction.” The technical monitor was Dr. Christine VanZomeren.

The work was performed by the Ecological Resources Branch (EEE) of the Ecosystem Evaluation and Engineering Division (EE), US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Mr. Joey Minter was chief, EEE; Mr. Mark D. Farr was chief, EE; and Dr. Jennifer Seiter-Moser, EEE, was the technical director for the Aquatic Nuisance Species Research Program (ANSRP). The deputy director of ERDC-EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmond J Russo Jr.

COL Christian Patterson was the Commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

1.1.1 HAB causes

Harmful algal blooms (HABs) and coastal hypoxic zones are evidence of cultural nutrient enrichment (Smith 2013) affecting public health and water supplies, aquatic ecosystem health, and economic well-being (National Science and Technology Council 2016). The ecological phenomena driving aquatic and marine algal productivity are natural responses to enriched nutrient status recognized for more than a century and are quite well understood in general (Smith 2013). Many natural background factors like watershed area, geology, and land use affect nutrient status in lakes, rivers, and coastal waters, but human development has significantly altered water and nutrient transport in the United States. Urban regions have significant point-source nutrient enrichment from municipal sewage treatment plants and industry, and non-point storm sewer effluent with lawn fertilizer and pet waste (Hobbie et al. 2017). Agricultural regions in the US Midwest and Mississippi Alluvial Valley have significant non-point source nutrient enrichment from land conversion, chemical fertilizer uses, and manure applications (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2015; Jones et al. 2018; Saad and Robertson 2019). Landscape scale land cover replacement of prairie to crops and wetland drainage to support row crop agriculture changed the nature of Midwest nutrient dynamics from one of natural nutrient transformation in prairie soils, wet prairies, and wetlands to one of nutrient transport where nutrients move rapidly through cropland soil to drain tiles, ditches, and streams with little opportunity for nutrient regulating processes to occur (Kumar et al. 2018). Recognition of the far-reaching impacts of Midwest agriculture led to establishing 45 percent nutrient reduction objectives for surface waters feeding the Gulf of Mexico (MR/GM Watershed Nutrient Task Force 2008). Similarly, a US Action Plan for Lake Erie developed integrated strategies for federal and state agencies to address phosphorus reduction objectives (US EPA 2016).

1.1.2 HAB impacts

Ecosystem impacts of HABs, and hypoxia include direct effects of algal toxins or perturbation of aquatic systems leading to temporary or long-term ecological impacts. Some algal blooms include toxic strains that produce cyanotoxins including neurotoxins, hepatotoxins, dermatoxins, and others that affect the stomach or intestines (US Centers for Disease Control and Prevention: https://www.cdc.gov/habs/illness-symptoms-freshwater.html). Marine HAB toxins are well known because of human illness associated with contaminated fish and shellfish (Anderson et al. 2000; Sellner et al. 2003; Ralston et al. 2011). Human illness from freshwater algal blooms includes respiratory, rash, gastro-intestinal disorders, and occasional severe symptoms depending on exposure pathway and duration (Stewart et al. 2006; Carmichael and Boyer 2016), but pet, livestock, and wildlife deaths do occur (Stewart et al. 2008).

Aquatic ecosystem impacts of HABs are typically seasonal, occurring in summer heat and low flow periods and influenced by many factors, especially high phosphorus concentrations (Havens 2008). Ecological response and impacts from bloom formation include (Havens 2008)

- Reduced water transparency blocking light and limiting other photosynthetic activity,
- Elevated pH causing lethal and sublethal impacts to fish,
- Reduced CO_2 altering phytoplankton competition,
- Toxin production impacting fish and wildlife,
- Increased algae size which reduces zooplankton grazing.

When algal blooms collapse, microbial production increases and causes hypoxia/anoxia and increased ammonia concentrations that have sub-lethal and lethal impacts on fish and other biota that displaces them from affected areas (Havens 2008).

Socioeconomic impacts of marine HABs are better understood than freshwater HABs because of the human health risks from seafood. The impact of HABs was estimated to be $450 million in 2000 ($618 million in 2020 dollars) with about one-half attributable to public health and one-third attributable to commercial fisheries impacts (Anderson et al. 2000). Ralston et al. (2011) estimate annual costs of marine pathogens and toxins to be $950 million, with $350 million due to known pathogens, $300 million to unknown origins, and $300 million due to gastro-intestinal illness from beach recreation. Costs of freshwater HABs affect tourism, property value, recreation/fishing, drinking water treatment, and monitoring and management adding up to $272 million annually for

Canadian waters (Smith et al 2019). DeRose et al. (2021) estimated $142 million annual economic impact to Lake Erie communities affected by HABs. A $2.2 billion estimate of the costs of freshwater HABs across the US attributed most loss to property values and recreational use (Dodds et al. 2008).

1.1.3 HAB prevention

The cultural nutrient enrichment driving increased incidence of HABs is a cumulative effect that overenriches surface waters with excessive nutrient loads from sewage, industry, and agriculture. The history of the impacts and need to manage sewage to protect human health in US cities is beyond the scope of this review, but there are many anecdotes of “dead rivers” downstream from cities during the Industrial Revolution to the 1920s when collection and treatment systems were developed. Sewage, slaughterhouse waste, livestock waste, logging waste, and many other organics fostered bacterial decomposition causing oxygen depletion and significant loss of aquatic organisms. The impacts were met with treatment technology and regulations that grew with population size. The 1972 Federal Water Pollution Control Act was developed in response to post World War II surface water degradation and public awareness of poor water quality. The “Clean Water Act” was very successful controlling municipal waste and point source pollution in the 1970s–1980s, but HABs rebounded in the 1990s (Bricker et al. 1998; USEPA 2016; National Science and Technology Council 2016) because nonpoint source (NPS) nutrient enrichment was high and increased with tile drainage in agriculture. Midwest row crops and animal agriculture contribute significant phosphorus loading which is significant disturbance in freshwater systems (Sharpley et al. 2003) and nitrogen loading which is a significant disturbance in marine systems (Rabalais and Turner 2019).

HAB control and treatment includes watershed and waterbody treatments to address the cause and symptoms (Paerl et al. 2016; Paerl and Barnard 2020). Watershed management includes controls on point source eliminations and increased attention to NPS nutrient enrichment by establishing Total Maximum Daily Load (TMDL) regulations to improve surface water quality. The TMDL process identifies limits for water quality impairments and recommends agricultural best management practices (BMPs) like precision farming, edge-of-field wetlands, buffers, tile drain controls, and other treatments to reduce sediment and nutrient transport. Midwest states have implemented watershed-based planning to address

NPS nutrient reduction and stream habitat quality. There have been decreases in suspended sediment and phosphorus in Upper Mississippi River tributaries (Kreiling and Houser 2016).

HAB control and treatment is often focused on individual lakes (Paerl et al. 2016). Reservoir operations can be adjusted to increase flushing or promote beneficial emergent wetlands that sequester nutrients (Herman et al. 2017). Vertical mixing circulates water and oxygenates the hypolimnion to increase microbial activity that consumes accumulated organic matter and moves cyanobacteria cells below the photic zone (Visser et al. 2016). Chemical treatments are an acute response to kill algal blooms with copper sulfate, hydrogen peroxide, and other compounds. Treatments like lime, alum, ferric chloride or sulfate, and ferrous sulfate can promote phosphorus precipitation and/or bind it into sediments (Medina et al. 2018). Dredging offers effective mechanical removal of sediment bound phosphorus but is expensive and challenging to implement (Medina et al. 2018). Biological control through food web manipulations with fish stocking or removal is another way to reduce sediment disturbance or increase algal grazing (Herman et al. 2017). A recently developed Harmful Algal Bloom Interception, Treatment And Transformation System (*HABITATS)* includes removal/collection of algal blooms with skimming, collecting and concentrating, and removal of algal biomass for beneficial use or landfill (Page et al. 2020).

1.2 Objective

Watershed phosphorus reductions have been seen in some places (Kreiling and Houser 2016), but current approaches to HAB prevention and nutrient reduction have not been sufficient to lower the risk of HABs; therefore, new tools to mitigate HAB drivers are required. Nutrient removal from surface waters to reduce HAB precursors has not been a significant research focus but new technology for efficient algal nutrient sequestration may offer opportunities to manage cultural nutrient enrichment. Paerl and Barnard (2016) suggest algal turf scrubbers (Adey 2011) as biological filtration systems to remove nutrients from surface water and animal effluents. Algal turf scrubbers (Adey 2011; Mulbry et al 2010) are raceway systems that support wild-stock, mixed filamentous algal species to sequester nutrients from shallow water or effluent flows over the algal matrix. In an economic analysis of HAB mitigation technology, DeRose et al. (2021) estimated 2,200 acres of turf scrubber area in a centralized treatment site would treat 50 percent of the Maumee

River flow and reduce total phosphorus by 40 percent. They emphasize these are novel systems and offered two costing scenarios using optimistic and conservative assessments, but the attached algae systems were estimated to save $12–$42 million per year.

Research on algal turf scrubbers for surface water nutrient remediation is limited but innovations on the theme are being implemented in municipal wastewater treatment plants. The objective of this report is to highlight emerging algal water treatment technology and explore its utility to cost-effectively reduce surface water nutrients and capture atmospheric carbon.

1.3 Approach

There are, in fact, several types of algal production systems developed for biofuel research and the food and pharmacology industry that are being repurposed for wastewater treatment as phosphorus effluent limits are being reduced and sustainable treatment methods are sought. This review of algal production systems will summarize emerging algal water treatment technologies and consider their potential to effectively sequester nutrients and atmospheric carbon from eutrophic Corps of Engineers reservoirs while producing useful biomass feedstock using solar energy.

2 Algae Beneficial Use in Society

2.1 Algae in human and animal health and nutrition

Algae have been used for nutrition in China for thousands of years, and their use has increased in food, pharmacology, cosmetics, proteins, pigments, bioactive substances (Bleakley and Hayes 2017; Sharma and Sharma 2017; Hemantkumar and Rahimbhai 2019), fuel (DOE 2016), animal feed (Sathasivam et al. 2019), fertilizer (Gimondo et al. 2020; Baweja et al. 2019), and wastewater treatment (Paddock 2019). More recently, algae have been used as health food in Japan, Taiwan, and Mexico (Sathasivam et al. 2019). Commercial products include tablets, capsules, and liquids and blends with numerous products, with *Sprirolina* and *Chlorella* dominating the market. Sathasivam et al. (2019) provides an extensive review of the nutritional and health benefits of these species that have achieved commercial scale with sales exceeding $38 billion. Hemantkumar and Rahimbhai (2019) estimated $6.5 billion global market for microalgae products. Several authors speculate on the value and growth potential for algal nutrition to meet the needs of growing populations seeking sustainable food resources (Bleakley and Hayes 2017; Koyande et al. 2019a).

The list of products derived from algae is quite extensive (Spolaore et al. 2006; Bleakley and Hayes 2017; Caporgno and Mathys 2018; Koyande et al. 2019a; Sathasivam et al. 2019). Sathasivam et al. (2019) provides a comprehensive list of microalgae metabolites being used for commercial purposes including: amino acids, antioxidants, many carotinoids, glutathione, glycerol, lipids (triglycerides and hydrocarbons), polysaccharides, several polyunsaturated fatty acids, proteins, sterols, toxins, and vitamins. Lipids are a high energy resource sought for biodiesel production, but algal biofuel has not become cost competitive with fossil fuels. Therefore, the algal biorefinery approach to extract multiple high value algal components has been proposed (DOE 2016; Sharma and Sharma 2017; Koyande et al 2019b). There are several models where industrial waste nutrients feed algae, which may be supplemented with flue gas CO_2, to produce at least nine high value algae derived products (Koyande et al 2019b). The process can sustainably manage waste and may be eligible to earn carbon capture and nutrient trading credits in addition to product revenue.

2.2 Algal bioenergy

A 2016 US Department of Energy (DOE) biofuel technology review provided a brief history of microalgae biofuel research development (DOE 2016). Algal biofuel investigations began in the 1950s when the carbohydrate fraction of algal cells was used as feedstock for anaerobic digestion to produce methane gas (DOE 2016). The discovery spurred more investigations on the lipid component for use in biofuels that gained increased importance during the 1970s oil embargo. The concept became a major push of the DOE Aquatic Species Program which lasted 1978–1996 and made significant progress on biodiesel strains, physiology, process development, and mass culture demonstrations. They collected over 3,000 strains to prioritize 300 for further research which discovered that nutrient limitations could enhance oil production. Harvests from open ponds and lipid extraction were cost-intensive activities. Overall, the program demonstrated the capability to produce biofuels, but the technology was not cost effective compared to 1970s, or current, oil prices.

From 1996 to 2008 several agencies, including Department of Defense (DoD), funded research to develop algal biofuels. In 2008, DOE formed the Bioenergy Technologies Office, Advanced Biofuels Initiative and in 2010 the Advanced Algal Systems Program. Research advanced through a group of four private-public Algal Biofuels Research Consortia Initiatives from 2009–2014, which in 2010 included funding three integrated biorefineries focused on algae cultivation and processing. Addressing challenges ahead, the DOE review acknowledges the great potential for algal feedstocks, but also recognizes the challenges of integrating new production approaches to established energy and agricultural systems. The 2016 Bioenergy Technology Review summarized the extensive research and knowledge gained in

- Algal biomass, genetics, and development
- Resources for algal research
- Algal biomass
- Harvesting and dewatering
- Extraction of algae
- Algal biofuel conversion technologies
- Commercial products
- Distribution and utilization
- Resources and sustainability
- Systems and techno-economic analysis

The DOE National Algal Biofuels Technology Roadmap states that there are advantages to algae-based wastewater treatment, including “potential to treat agricultural drainage and eutrophic water bodies, 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 green-house gas benefit)” (DOE 2010). This document emphasizes the value of partnerships and supply chain integration to cost-effectively acquire water, nutrient, and CO_2 resources. The Corps of Engineers operates hundreds of water projects managing nutrient rich surface water that could fuel bioenergy and other biomass production while cleaning eutrophic lakes and rivers. DoD US installations operate approximately 100 municipal-scale wastewater treatment facilities (SERDP/ESTCP: https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Wastewater-and-Drinking-Water#:~:text=DoD%20provides%20drinking%20water%20to,the%20operation%20of%20the%20installation) that could incorporate algal treatment systems to offset their carbon use.

2.3 Wastewater treatment

Paddock (2019) provided a brief history of microalgae use in wastewater treatment beginning in the early 1900s when algal nutrient uptake and oxygenation properties were recognized. The “Green Revolution,” US population growth after WWII, and the environmental movement spurred interest in new environmental engineering and science including microalgae wastewater treatment. Photobioreactor and open pond algal production system designs from the 1950s are still in use today. Research grew to integrate food and other resource production with wastewater treatment. Pressure to reduce marine and freshwater nutrient enrichment led to development of Smithsonian Institute Algal Turf Scrubbers™ (Adey et al. 2011) for research, aquaculture, and aquaria applications before being scaled up to field-scale applications in the Chesapeake Bay watershed (Mulbry and Kondrad 2010), Florida (Sano et al. 2005), and California (Craggs et al. 1996). Paddock (2019) also reviews the microalgae biofuel history and concludes that the desire for sustainability and continued technological development and process integration may promote further development of microalgae treatment systems.

Abdel-Raouf et al. (2012), Abinandan and Shanthakumar (2015), Diniz et al. (2016), and Goncalves et al. (2017) are other authors that have reviewed the potential for wastewater treatment and biofuel or other productions. Current applications of the technology include open ponds (Park et al. 2011; Thomas et al. 2019), algal biofilm systems (Gross et al. 2015), rotating algal contactors (Johnson et al. 2018; Wollman et al. 2019), and photobioreactors (Placzak et al. 2017, https://www.clearaswater.com/solution).

2.4 Biofertilizer

Chemical fertilizers in row crop agriculture are responsible for much of the surface water impairment leading to HABs because they are applied in large doses and are not stable in the environment. Biofertilizers are an alternative that had been a standard practice implemented as composting and manure use on crops. Commercial sales of microbial biofertilizer began in 1895 and was soon followed by the discovery of the utility of blue-green algae in agriculture (Ju et al. 2018). Cyanobacteria nitrogen-fixing has been recognized as a component of rice paddy culture since 1939 and has become a refined and well-documented practice (FAO 1981; Whitton and Roger 1989). Biofertilizers are also stable in the soil (Solovchenko et al. 2016; Baweja et al. 2019; Gimondo et al. 2020) and deliver nutrients in forms available to crops (Alobwede et al. 2019; Siebers et al. 2019). There are reviews of the benefits of algae in agriculture (Renuka et al. 2018; Win et al. 2018) that document

- Nitrogen fixation
- CO_2 fixation
- Solubilization of macro- and micro-nutrients
- Production of growth hormones
- Biocidal properties
- Soil health/land reclamation.

Solovchenko et al. (2016) document the role of microalgae in recovering phosphorus from wastewater for use in agriculture.

Biofertilizer, therefore, could be a simple and environmentally beneficial use of algal biomass if it can be cost-effectively grown, harvested, and transported. In a wastewater or surface water nutrient treatment chain, biofertilizer would be a reliable disposal alternative for biomass that may not meet commercial product standards. Wastewater, for example, would need to be monitored for heavy metals or pharmaceuticals that may bioaccumulate in algae (Mironiuk and Chojnacka 2018). Surface water may have high concentrations of suspended solids that would need to be washed in a commercial product treatment process, but not a fertilizer product treatment process. Algal turf treatment systems tend to have a higher ash content from high diatom concentrations or sand particles in water (Liu 2017; de Souza et al. 2020) which may be a detriment in commercial applications but irrelevant or beneficial in a biofertilizer. Assuming algae could be grown in livestock coproduction or in rural surface waters, it could be produced and used in small geographic regions with local biofertilizer markets to reduce transportation costs and energy use. It may also empower economic development in underserved rural communities.

3 Algal Growth Systems

There are four general approaches to algal culture: open ponds, photobioreactors, immobilized algae, and biofilm systems. Each system requires abundant space, water, nutrients, CO_2, mixing, and light. Predation and contamination risks vary among the algal culture techniques. A National Research Council (2012) review identified the following as highly important concerns for the sustainability of algal biofuels:

- Energy rate of investment
- Greenhouse gas emissions
- Land and water use, and
- Supply of nitrogen, phosphorus, and carbon dioxide

Eutrophic surface waters alleviate some concerns because they provide abundant water and nutrient resources for algal biomass production. Also, high nutrient concentrations occur in rivers in Midwest agricultural regions where land resources for algal treatment systems can be found as compared to municipal treatment plants. Appropriate technology can be used to minimize energy use and carbon inputs in growth systems. The energy rate of investment for biofuel is not of primary importance because the objective is clean water, not fuel. In surface water treatment, the income from biomass products could offset the cost of investment, potentially exceeding it, to incentivize private sector investment with access to low-cost raw materials in the form of agricultural runoff.

3.1 Open ponds

Open ponds (Figures 1–3) are the most common algal cultivation systems, emerging in the 1950s to grow *Chlorella* for food. Big shallow ponds, tanks, circular ponds, and raceway ponds are common cultivation systems, with raceway ponds being most common and productive (Kumar et al. 2015; Young et al. 2017). Kumar et al. (2015) review factors affecting algal pond productivity which has much higher algal concentrations than nature but is still dilute and requires significant space for shallow pond construction to treat large volumes of wastewater or grow biomass. Equipment and power usage are also important factors; and air is used to circulate water much cheaper than mechanical equipment. Mixing suspended algae is important to assure abundant nutrients and light. Since water does not diffuse gas efficiently, CO_2 augmentation is necessary to optimize algal productivity. Colocation with industry in a biorefinery concept is an ideal source of flue gases to enhance algal production. Algae predators and contamination are critical risks that can destroy algal crops. Algal polycultures have been recommended to increase productivity and prevent colony collapse from contamination and grazing (Goncalves et al 2016; Newby et al. 2016). Algal productivity varies with climate and season but estimates from 5 to 45 g dry weight/m^2/day (Park et al. 2011; Handler et al. 2012; Kumar et al. 2015; Hong et al. 2016) were found in literature. Nitrogen and phosphorus removal efficiency ranged from 60–99 percent in a review of wastewater treatment algal ponds (Goncalves et al. 2016). Large-scale algae farms have been demonstrated and shown to produce valuable crops, but more lab-to-field conversions are needed to create the production potential to drive algae industry potential (White and Ryan 2015).

Figure 1. A field of algae raceway ponds. (Credit: Pacific Northwest National Laboratory).

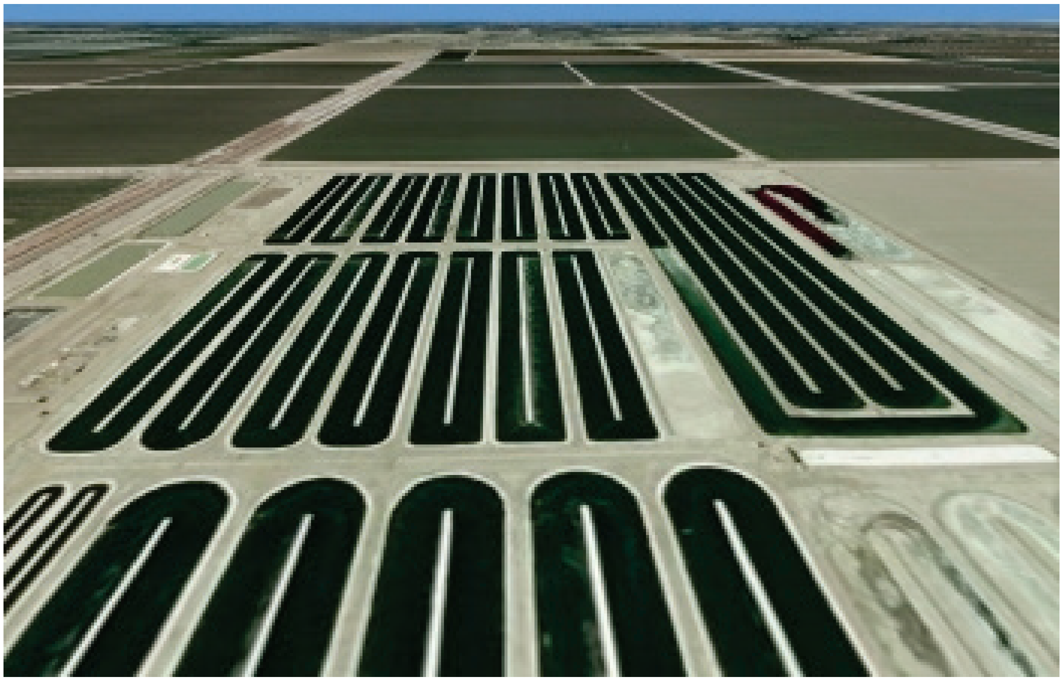


Figure 2. Sapphire Energy raceway pond.

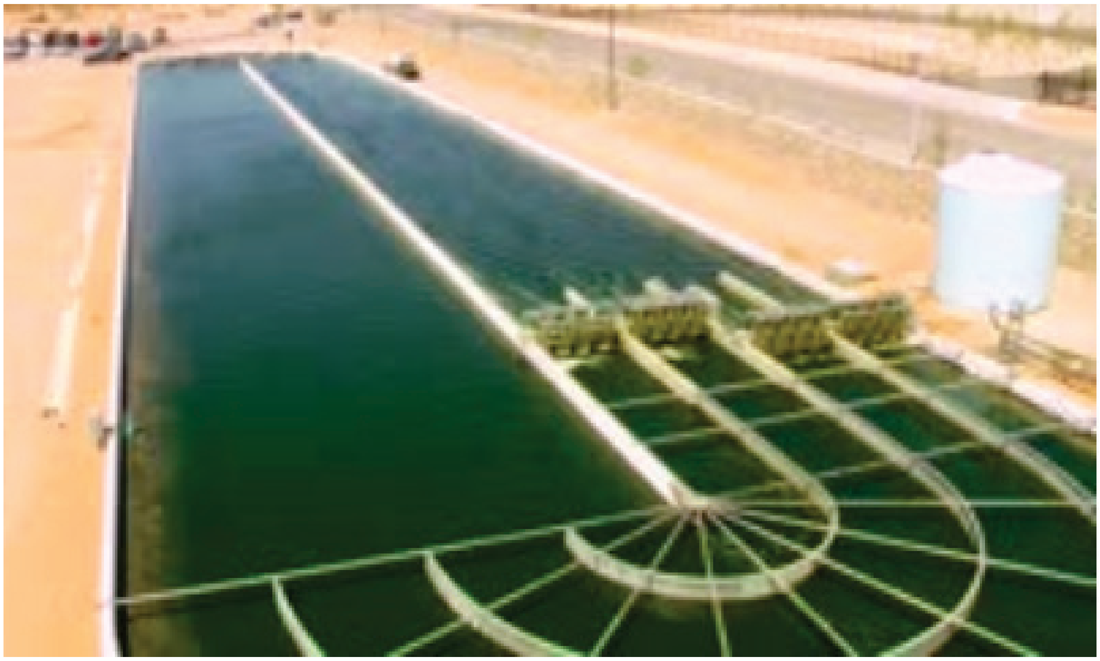
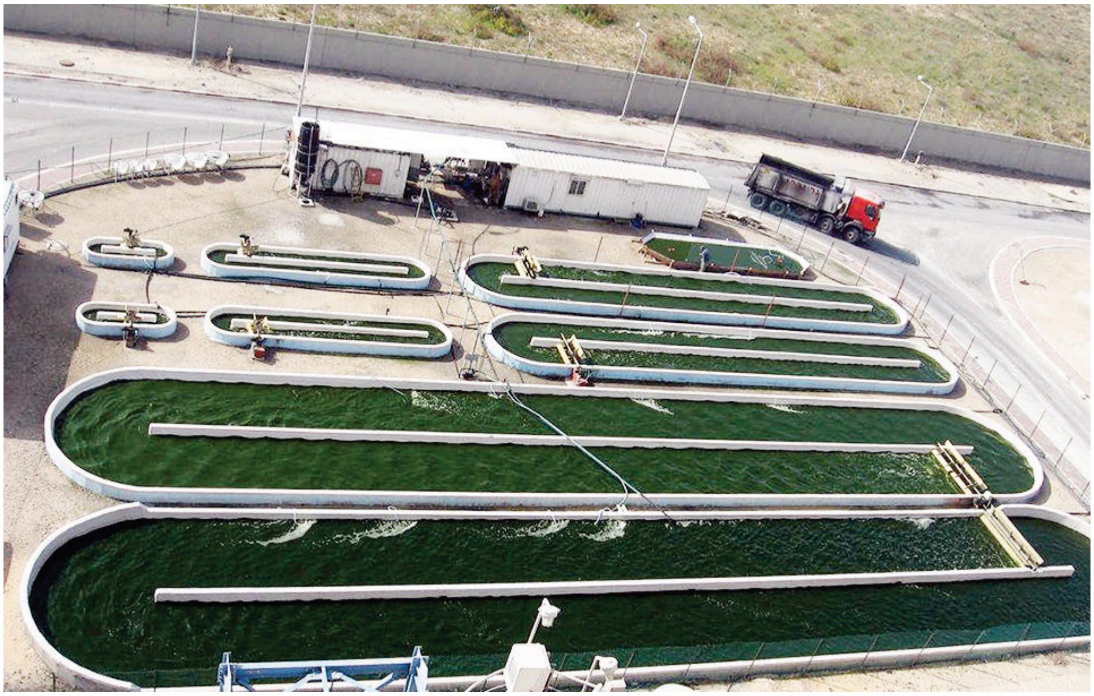


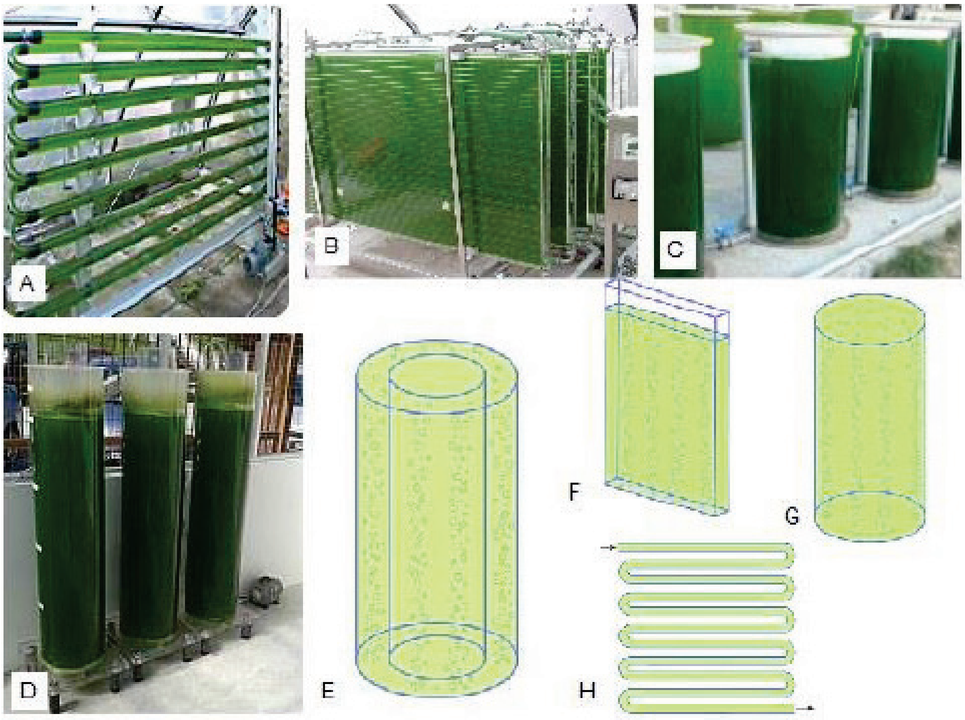
Figure 3. Multiple experimental raceway pond units show scaling options. (Photo courtesy of the US Department of Energy Renewable Energy Laboratory).



3.2 Photobioreactors

Algal photobioreactors (Figure 4) are closed systems that offer greater level of control than open ponds and can maintain monocultures of desired algal species (Placzek et al. 2017). They are costly and complicated to build, operate, and maintain but have higher productivity and algal density than ponds (Kumar et al. 2015). Although column photobioreactors have good constructability and operation, their poor light performance reduces its suitability for buoyant species. Flat panel reactors have large surface to light ratio and are relatively inexpensive to build and operate. Large operations require significant infrastructure and there is risk of fouling, overheating, and sloughing. Tubular photobioreactors offer high light exposure, high productive, and relatively low cost. Installation is complex, conditions may vary through the system, and biofilm on the tubes is a problem. They are most useful for producing high value monoculture products and cultures for pond seeding. The University of Kentucky has a substantial photobioreactor demonstration for flue gas CO_2 mitigation (https://www.uky.edu/bae/sites/www.uky.edu.bae/files/AEU-101.pdf).

Figure 4. Algae photobioreactor examples: (A) tubular, (B) flat panel, (C) column, (D) annular, (E-H) diagrams of each. (Source: Satpati and Pal 2018).



3.3 Algal Turf Scrubbers®

Algal Turf Scrubbers® (ATS™) are shallow raceway systems to promote growth of wild stock, mixed algae turf communities to uptake nutrients from municipal, agricultural, and industrial wastewater or eutrophic surface water (Figure 5; Craggs et al. 1996; Mulbry et al. 2010; Adey et al. 2011). They have been implemented in municipal (Craggs et al. 1996), agricultural (Mulbry et al. 2008a), and surface water (Mulbry et al. 2010) applications. Water flows over an attached algae matrix which metabolizes macro- and micronutrients into the algal biomass which is harvested weekly for beneficial use. Clean water is returned to the waterways, so there is no water use beyond evapotranspiration. Harvest is important to maintain high productivity and manage invertebrate grazers (Adey et al. 2011). Algal productivity rates vary widely from 1 to 20 g/m^2/day among studies and there are considerations for project footprint area versus growing area as different vertical and rotating designs are developed (Gross et al. 2015). Rotating biofilm (Figure 6) and rotating algal contactors (Figure 7) compress more algal growth area into smaller footprints compared to ATS raceways. Rotating algal biofilms achieved 45 g dry weight/m^2/day for its project footprint which uses vertically oriented cotton sheets rotating through a wastewater or surface water sump (Gross et al. 2015). Algal biofilms have high nitrogen and phosphorus nutrient removal efficiency, achieving 80 – 100 percent in scale demonstrations (Zhao et al. 2018). ATS also had high removal efficiency of 70–90 percent at low nutrient loading rates (Mulbry et al. 2008a) which may be common in surface water applications. Rotating algal contactors (i.e., Algaewheel) have no mechanical parts and low energy consumption because air bubbles move the growth media (Johnson et al. 2018). Local nutrient and climate conditions are an important consideration for system design so in situ pilot studies are required to estimate the performance of new systems.

Figure 5. Large-scale algal turf scrubber demonstration in Ocala, FL (Source: Hydromentia, Ocala, FL).

Figure 6. Rotating Algal Biofilm (RAB) system developed by Gross-Wen Technologies is a space-efficient design for algal production, and their harvest and biofertilizer production is integrated for efficient biomass utilization. (Source: Gross-Wen Technologies, Slater, IA)

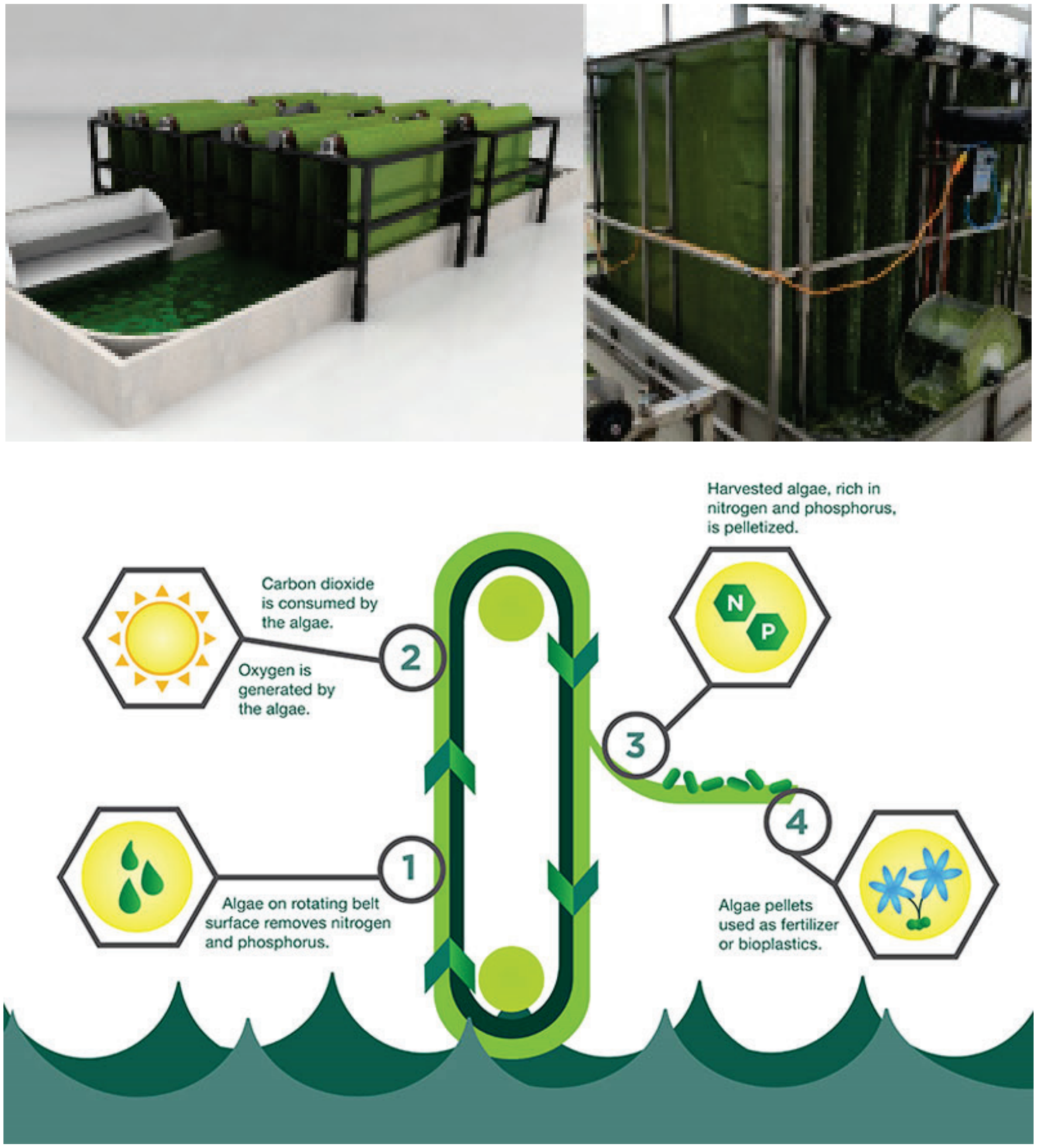
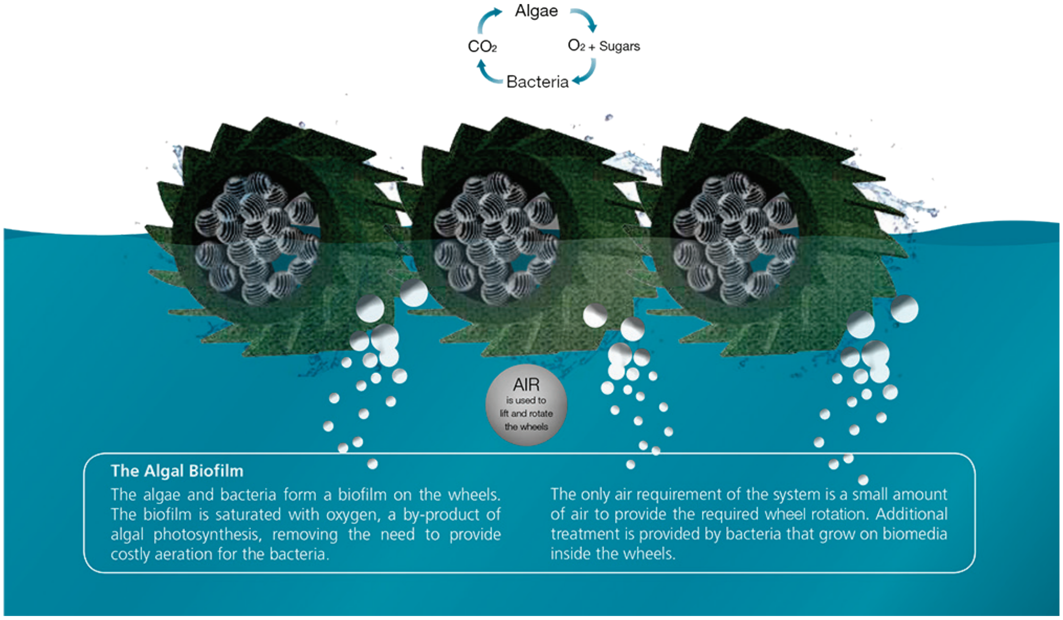


Figure 7. Algaewheel® rotating algal contactors are energy-efficient air-powered biofiltration systems for small municipal systems (5,000–250,000 GPD) (Source: OneWater, Cary, NC).



The Algal Biofilm

The algae and bacteria form a biofilm on the wheels. The biofilm is saturated with oxygen, a by-product of algal photosynthesis, removing the need to provide costly aeration for the bacteria.

The only air requirement of the system is a small amount of air to provide the required wheel rotation. Additional treatment is provided by bacteria that grow on biomedia inside the wheels.

4 Potential for Algal Surface Water Treatment at Corps Projects

Algal culture techniques have been developed for several purposes over recent decades. The industry has developed markets in the food, nutrition, and pharmaceuticals and is advancing to develop refined pigments and other biotechnology products. The biofuel life-cycle cost analysis (LCA) has never been competitive with fossil fuels, but several technological approaches for bioenergy production are well developed and still advancing. Algal treatment technology has thus moved toward wastewater treatment where more stringent discharge requirements and a desire for sustainability and resource recovery support the cost of algal treatment systems. Integration of wastewater streams and algal production is an important concept to manage costs and resource use. ATS technology for surface water nutrient reduction has been postulated and tested in the Chesapeake Bay watershed (Mulbry et al. 2010) where it achieved a nutrient sediment reduction accreditation recommendation from a Chesapeake Bay Program BMP review panel (Bott et al. 2015). A large-scale ATS demonstration in Florida agriculture exceeded treatment wetland nutrient reduction for lower cost (Adey et al. 2011), but treatment wetland alternatives were selected for large-scale implementation. Can algal treatment systems effectively sequester nutrients to reduce algal blooms in Corps of Engineer reservoirs and rivers?

Corps lake managers are managing watershed sinks that have been accumulating nutrients for decades as water quality has degraded to acute levels for public and ecosystem health. Lake managers do not typically have specific authority or requirements to manage water quality, but they can help plan and implement land management practices in watersheds and on project lands to reduce nutrient loading. They also have reservoir operational controls, promote wetland development, and build treatment wetlands to increase nutrient processing in lakes. Algal treatment systems for surface water nutrient reduction provides a novel approach to sequester nutrients from surface water using sustainable biotechnology. Ideally, biomass utilization potential would drive sufficient economic incentive to entice private sector investment in surface water treatment systems. Alternatively, Corps managers can evaluate the cost:benefit of investing in nutrient remediation technology.

DeRose et al. (2021) modeled the cost:benefit of Maumee River nutrient reduction and demonstrated that a 2,100-acre centralized ATS system ($10 million), or 4,600 acres in a decentralized ($21 million) system, would reduce phosphorus loading 40 percent and prevent $12 - $47 million annual HAB-related economic losses in Lake Erie. They did not include the potential value of the biomass in their estimates. They accounted for property value, recreation, tourism, and water treatment costs associated with HABs. The Maumee River watershed (6,300 mi^2) is much larger than many Corps lakes, so there may be a subset of Corps projects that could be cost effectively managed with algal bioremediation. Harsha Lake (East Fork Lake), Ohio (2,100 surface water acres) is one example of many eutrophic Midwest lakes that can serve as a model for ATS evaluation. The subwatershed is 500 mi^2, or <1/10th the size of the Maumee, so would a treatment system be comparably smaller at 200 acres and $1 million?

There are too many uncertainties to authoritatively determine whether algal systems can remediate eutrophication in Corps lakes. Most whole-lake algae and nutrient treatments are expensive and short-lived. Treatment wetlands are another nature-based approach to nutrient reduction that have been implemented in upland agriculture BMPs and lake remediation programs. They have good nutrient removal performance, but have construction, operations, and long-term maintenance costs that must be considered. Without sediment and biomass harvest plans, wetland management units accumulate sediment and plant biomass and fill over time. Conversely, emerging algal water treatment systems are low maintenance and, additionally, have the potential for biomass sales to offset construction and operating costs.

4.1 Nutrient management alternative qualitative cost assessment

A simple qualitative assessment of reservoir nutrient management alternative treatment volumes and rates, treatment implementation and operating costs, longevity, co-product potential, and nutrient trading potential can help compare common HAB treatment alternatives (Table 1). Corps planning always considers a future without action plan which for most lakes implies continued nutrient enrichment leading to known outcomes and costs summarized in Section 1.2.

Table 1. Qualitative assessment of reservoir nutrient management alternatives.

Reservoir Nutrient Management Alternative	Area/Volume Treated	Treatment Rate	Reliability/ Longevity	Cost	O&M cost	Coproduct Potential	Nutrient Trading Potential
Future without action	None	None	Continue decline	Impaired water/ recreation	Lost revenue, maintenance	None	None
Watershed management (BMPs & cropland set asides)	Whole lake	Slow	High	High	Moderate	Low	High
Dredging	Small – whole lake	Fast	Moderate	High	Moderate	Low	Low
Mixing	Small – whole lake	Moderate	Moderate	Moderate	Moderate	None	None
Aeration	Small – whole lake	Moderate	High	Low	Moderate	None	None
Chemical treatment (i.e., alum)	Small – whole lake	Fast	Low	High	Low	None	None
Ultrasound	Small – whole lake	Fast	Moderate	Low	High	None	None
Reservoir wetland management	Whole lake	Slow	High	Low	Low	Habitat	Moderate
Constructed treatment wetlands	Whole lake	Moderate	High	High	High	Habitat	High
Floating treatment wetlands	Small – whole lake	Slow	Moderate	High	High	Habitat	Moderate
Algal turf scrubbers	Whole lake	Moderate	High	High	High	High	High

Dredging is a well-known sediment and nutrient management treatment (Medina et al. 2018) practiced on small ponds to large public reservoirs like a recent Lake Decatur dredging which cost $94 million to restore 30 percent capacity after a 2011 project completion (11 percent restored) and a 1995 project completion (6 percent restored) (Source: City of Decatur, Illinois http://76.12.68.44/documents/LakeDecatur-dredging-Stevens-1115.pdf). Treatment benefits are exhibited after dredging disturbance diminishes, but shallow ecosystems and benthic communities will take time to recover. Regulatory compliance, dredging and dredged material management is expensive and project longevity depends on the degree watershed management can reduce sediment transport to reservoirs. Beneficial uses for sediment can be investigated to reduce management costs. Nutrient credits might be possible, but deep sediment nutrients are unlikely to be disturbed without dredging and digging them up remobilizes buried nutrients.

Watershed BMPs are a distributed, diffuse solution to reduce nutrient loading to lakes which should be the primary objective for lake-wide water quality benefits. They can be reliable for reducing nutrients if well targeted (Tomer et al. 2013; McLellan et al. 2015) but require permanent land set asides or alternative crops. Routine agricultural management for some practices have co-product potential like hay or biogas and there is potential for nutrient and carbon trading (Perez et al. 2009). Watershed planning tools are available to help prioritize BMP implementation (Tomer et al. 2015).

Hypolimnetic mixing with aeration or pump systems is a method to reduce lake stratification, increase oxygen content, and mix algal cells below the photic zone which encourages beneficial green algae over cyanobacteria (Visser et al. 2016). Lake aeration uses air pumped through submersed diffusers to circulate hypolimnetic water to the surface of lakes where gas exchange occurs. Various pump systems have also been used to move algal cells upward from or downward to the hypolimnion where cyanobacteria are light limited and green algae outcompete them. The mechanical treatment area depends on lake morphology but could mix large uniform basins. Implementation costs would be high, but operation costs should be low. The benefits degrade rapidly if the mechanical intervention is interrupted. Nutrients and gases are exchanged leading to lower phosphorus concentrations and increased hypolimnetic oxygen (Medina et al. 2018) which may improve benthic habitat for macroinvertebrates (Pastorok et al. 1982).

Chemical treatments include chemicals to kill algal cells and flocculants to precipitate and bind phosphorus in sediments. They are generally successful for short periods only and are very expensive for large areas and repetitive treatments (Herman et al. 2017). They can be used more effectively in precision applications such as wetland treatment chains for example. Sonic treatments to disturb algal floatation and sink algal cells below the photic zone have been demonstrated in the lab (Kotopoulis et al. 2009) but have not been evaluated in large-scale and long-term applications (Ghernaout and Elboughdiri 2020). Nutrients will be liberated upon cell death which may increase nutrient cycling. Zhen et al. (2017) identifies interactions that liberate heavy metals from sediments which is an unacceptable risk which should be evaluated. None of the in-lake treatment has coproduct or nutrient trading potential.

Biological approaches to HAB control focus on nutrient reduction through increased plant and microbial productivity by promoting wetland and riparian communities, constructing treatment wetlands, installing floating treatment wetlands, or perhaps constructing algal water treatment systems. Project placement is usually spatially optimized for the greatest performance to treat inflows, near wastewater inflows, or at hydraulic restrictions like causeways and bridges in reservoirs. Reservoir Environmental Pool Management can be used to optimize delta wetland and riparian habitat where operation plans offer flexibility (Blaan et al. 2016; Calomeni et al. 2022). Success is dependent on annual hydrology, but slight operational changes might influence large areas to provide habitat, sediment, and nutrient reduction benefits for low cost. If downstream nutrient reductions can be achieved and documented, then the practice might be eligible for nutrient trading credits. Treatment wetlands are well understood and can treat large volumes of water with high reliability in controlled systems. Wetland treatment chain construction for Grand Lake St. Mary's, Ohio tributaries cost about $2 million each for tributaries feeding the lake and require water management and maintenance of alum injection systems. Treatment wetlands are expensive to build and operate but provide habitat and can participate in nutrient trading.

Floating treatment wetlands are platforms that support emergent aquatic plant growth in otherwise unsuitable locations due to turbidity, variable water levels, swift currents, or herbivory (Headley and Tanner 2011). At least 6 percent of the lake area should be covered for lake-wide response, but they can be arranged to treat lake inflows for a whole lake influence. They can also be arranged as wind-wave barriers to create sheltered aquatic areas to reduce turbidity and promote submersed aquatic plants for a larger area of influence. They are high cost and require maintenance but are durable and provide habitat benefits where physical constraints like turbidity, depth, water variability and waves limit natural wetlands. They were recommended for water quality credits in the Chesapeake Bay nutrient trading program (Schueler et al. 2016).

ATS are discussed above to show they can be used to reduce nutrient concentrations in reservoir surface water. Algal treatment systems are scalable and could be designed to treat large volumes to influence lake-wide water quality. Large ATS treatment systems would be expensive to build and operate, but they should be reliable and durable to operate indefinitely with maintenance. ATS are the one nutrient treatment system that has high biomass co-product potential to offset operating cost. Nutrient rich WWTP outflows and eutrophic surface water provide “cost advantaged” inputs which minimize or eliminate the cost for raw materials to grow biomass. Algal systems can be used to treat water, farm algal biomass, and simultaneously trade carbon and nutrient credits as an additional income stream.

4.2 Path forward

This review of algae-based surface water treatment systems is intended to help address the nutrient reduction challenge by introducing an innovative resource recovery technology with commercial profit potential. Significant, unresolved concerns regarding algal bioremediation at Corps projects include the potential algal productivity in local surface water and climate conditions (e.g., nutrient concentration, suspended sediment, temperature), performance and operational considerations for various growth systems (e.g., nutrient removal efficiency and harvest/maintenance schedule), water treatment objectives for system design and scaling, and biomass utilization. Determining the potential algal productivity in local waters can be investigated at one or multiple priority locations using small, pilot-scale demonstrations of algal culture systems. Demonstrations of ATS and rotating algal contactors could be completed in the following nutrient rich rivers:

- Upper Mississippi River
- Maumee River
- Florida site TBD
- Ohio reservoir TBD
- 2 additional Upper Mississippi River locations

Local partners at Corps projects and river research centers could be helpful in supporting research operation and maintenance; therefore, initial site selection must consider existing research facilities and Corps project sites. Spatial variability between sites would cover a range of water quality parameters including suspended solids, nutrients, and climate conditions experienced at Corps projects.

Pilot studies have not been designed pending the recommendations from this review, but relatively simple experimental designs can be implemented. An ATS study could use a standard pilot scale elevated trough flow-way design or a custom ATS raceway constructed from pond liner material on a 2% grade. Pilot studies could resolve many of the initial algae culture questions to determine whether more complicated algal treatment systems should be explored. Algal community composition and colonization rates could be established during early project implementation as the native turf becomes established. Water chemistry measurements of the inflow, through the flow-way, and at the outflow would be taken to characterize biogeochemistry throughout the ATS system. When mature, stable algal cultures are achieved, routine biogeochemistry monitoring a harvest schedule would continue through the growing season or year-round where possible.

Reservoir operations, objectives, and constraints would be evaluated concurrent with algal growth studies. Lake managers and stakeholders would help identify the appropriate level of nutrient reduction in reservoir watersheds, and local planning could consider available nutrient reduction alternatives like agricultural BMPs, septic system upgrades, point source control, wetland management/restoration, treatment wetlands, and algal treatment systems. The nutrient reduction objectives could be combined with local algal productivity studies to design algal treatment systems. Stakeholder involvement can help with algal biomass management. The multiple product potential for algal biomass is extensive and exciting. At a bare minimum, local farmers could help manage algal biomass as biofertilizer for improved soil health. One algal treatment system reviewed produces a dry, pelletized algal biomass product that can be handled for distribution like other commercial fertilizer.

Biomass production and management is complicated by start-up costs and supply-and-demand conflicts. The US Department of Energy has invested heavily in algal biofuel development, but due to the lack of demand for algal biomass, the systems required to manage large amounts of algal biomass do not exist. Thus, market development to grow supply, demand, and opportunity are warranted. Demonstrating the availability of a viable commercial biomass product may encourage the private sector to develop production systems that offset the cost of managing surface water nutrient enrichment.

Algal biomass utilization is already a component of ERDC research in the HABITATS algal bloom interception research where the biomass has been used to create biofuel in a hydrothermal liquefaction process (Page et al. 2019). Algal biomass from ATS systems could be integrated into the ERDC biofuel research as a sustainably produced and reliable supply of biomass. Treatment of acute HABs is becoming increasingly important but provides only episodic biomass inputs in locations where and when HABs occur. Long-term algal nutrient reduction systems (i.e., nutrient farms), conversely, would be fixed in place to mitigate the causes of HABs while producing a dependable supply of biomass to feed an emerging algal industry. There is potential to build on the HABITATS technology by adding algal treatment systems in-line with algae harvest systems. Coupling multiple technologies at spatially optimized fixed treatment nodes would provide the most efficient systems that could be built out to complete biorefinery facilities.

Algal biofertilizer could be a component of a reservoir watershed management plan if biofertilizer produced from watershed nutrient runoff is applied back to watershed soils. ERDC soil scientists and watershed hydrologists could collaborate to investigate changes in soil health, plants growth, and nutrient transport in algae amended soils. The prospect of biofertilizer as part of a watershed nutrient management plan is interesting, but realistic estimates of biomass productivity are needed to determine the amount of biofertilizer produced relative to the 20–100 pounds per acre (i.e., millions of pounds per watershed) of commercial nitrogen and phosphorus applied to row crops. One recent study investigated the value of algal biofertilizer in container crop growing systems where it performed favorably against commercial fertilizers (Gimondo et al. 2020) as observed in other studies (Mulbry et al. 2008b; Ju et al. 2018; Alobwede 2019; Baweja et al. 2019).

5 Future Research Recommendation

Algae-based nutrient reduction is a biological approach to achieve multiple National environmental objectives while producing commercial biomass products. Technology and processes developed for biofuel research are being cost-effectively applied to municipal wastewater treatment and there may be significant potential to use the approach on nutrient rich surface water. There have been several Algal Turf Scrubber pilot studies that help understand the performance of algal surface water treatment, but the newer technology has not been evaluated for surface water. More research is needed to determine whether the practice can achieve nutrient and carbon reduction objectives and produce a profit.

First, there is a need to evaluate new algal treatment technology described here in surface water applications. Pilot studies using small-scale systems can be implemented at one or more sites to establish surface water algal productivity and nutrient sequestration potential. Pilot studies would help evaluate challenges of working with turbid surface water, seasonal sediment and nutrient flux, and other factors. They could also estimate local algae production potential, biomass potential, biomass quality, and biomass utilization to design larger treatment systems.

Understanding the cost and benefits of a large algal treatment system is important to evaluate the feasibility of the technology in society. One or more locations should be identified to collaborate with local stakeholders to establish river, reservoir, or lake nutrient reduction objectives which would be used to design and estimate implementation costs and benefits of an appropriate treatment system. The stakeholders would include lake managers, water quality and wildlife specialists, the public, municipalities, farmers, and commercial partners. The exercise would help bound the scale of the nutrient reduction challenges in impaired reservoirs and rivers and use it to estimate resource recovery potential of algal treatment.

Biomass utilization is an important element of algal surface water treatment. Algal biomass conversion to biocrude is well understood but the biofertilizer and other product potential require more research and development. There is a lack of public awareness of the commercial potential for algae, but a growing biomass utilization community is changing that. For example, biorefineries are being developed to efficiently extract lipids, proteins, and polysaccharides used to manufacture of algal chemicals and polymers, biofuel, food, and feed. Algal biofertilizer is used in agricultural applications, but it could be greatly increased if proven to be cost-effective and beneficial to crops and soil health. Algal fertilizer growth and production might be managed as local agricultural cooperatives to create and distribute fertilizer products locally to achieve low transportation costs and local water quality benefits also. Research evaluating the social, economic, and environmental benefits of biofertilizer could support local solutions to global challenges.

Collaboration among government agencies and industry supporting algal technology is important to identify the unique environmental benefits of algae-based nutrient reduction. The DOE, Bioenergy Technology Office has been a leader in algae research, and they recognize the potential environmental benefits or harms growing algae. Their research has been adopted in the wastewater treatment industry where commercial algae treatment systems are used in municipal and agricultural waste management. The wastewater industry has adopted a “resource recovery” approach to their processes and algae is well-suited for their needs. USDA demonstrated algae benefits in livestock waste management decades ago, but agriculture has many untapped opportunities to manage animal waste with algae. One example currently in practice is to use algal treatment systems to reduce phosphorus in the waste stream from anaerobic digesters. Another could be to use dairy bedding sand rinse water to fuel algae production systems. The practice creates a chained treatment system that adds value at each step and creates a closed loop food and energy production system that captures carbon and stores it in soil and keeps nutrients out of surface water.

The Corps of Engineers should invest in algae research because of our role managing the Nation’s water resources and supporting the DoD Climate Adaptation Plan (Department of Defense 2021). These missions intersect with algae treatment systems that sequester surface water nutrients and atmospheric carbon in organic biomass feedstock useful for many purposes. This is a natural, nature-based approach to use water infrastructure to solve complex and widespread resource problems like harmful algal blooms, nutrient impaired drinking water, and reduced ecosystem goods and service output. USACE is active in watershed management and can use hydrologic modeling to optimize the location of infrastructure to optimize ecosystem service outputs. For example, Midwest levee and drainage districts move tremendous amounts of nutrient rich water that can be accessed to grow algal biomass and reduce nutrient transport to the Gulf of Mexico.

The idea to use “algae to fight algae” is in response to the Nation’s problems with surface water nutrient enrichment and climate change. It is holistic in that is considers an entire process chain to reduce nutrients in water and carbon in the atmosphere while creating value-added products. The use of the biomass as biofertilizer would have soil health benefits that could reduce future sediment and nutrient impairment and lock the carbon into soil. The technology is commercially available and is considered here in a different application to help solve the Nation’s nutrient impairment problem using private-public partnerships. The ERDC partnership with AECOM to develop and implement HABITATS is an example of the private-public partnership that could evaluate engineered algal treatment systems to prevent HABs rather than respond to them. The Corps of Engineers research in algal treatment systems could evaluate the ecosystem goods and service analysis of algal treatment systems in surface water infrastructure.

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14. ABSTRACT

Harmful algal blooms (HABs) and coastal hypoxic zones are evidence of cultural nutrient enrichment affecting public health and water supplies, aquatic ecosystem health, and economic well-being in the United States. Recognition of the far-reaching impacts of Midwest agriculture has led to establishing nutrient reduction objectives for surface waters feeding the Gulf of Mexico, Lake Erie, and many smaller water bodies. Municipal nutrient enrichment impacts have been addressed by increasing levels of sewage treatment and waste management through the Clean Water Act era, but HABs rebounded in the 1990s because of non-point source nutrient enrichment. HAB control and treatment includes watershed and waterbody treatments to reduce loading and address outbreaks. Systems to remove nutrients from impaired waters are expensive to build and operate. This review of algal production systems summarizes emerging algal water treatment technologies and considers their potential to effectively sequester nutrients and atmospheric carbon from hundreds of eutrophic reservoirs and DoD wastewater treatment facilities while producing useful biomass feedstock using solar energy. Algal water treatment systems including open ponds, photobioreactors, and algal turf scrubbers® can be used to grow biomass for biofuel, wastewater treatment, and commercial products. This review recommends continuing research on surface water nutrient reduction potential with algal turf scrubber productivity pilot studies, preliminary site design, and biomass utilization investigations.

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