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Review

Bioenergy from wastewater-based biomass

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Abstract: The U.S. Department of Energy (DOE) has stated that biomass is the only renewable resource that can supplant petroleum-based liquid transportation fuels in the near term. Wastewater is beginning to be viewed as a potential resource that can be exploited for biomass production and conversion to bioenergy. We suggest that using wastewater from municipalities and industries as a resource for cultivating biomass and combining wastewater treatment with the production of biomass for bioenergy would provide benefits to both industries. Two waste-based biomass production systems that currently have large nationwide infrastructures include: (1) wastewater treatment systems that can be used to cultivate algae biomass, and (2) land application/treatment systems for non-food terrestrial biomass. These existing infrastructures could be used in the relatively near future for waste-based biomass production and conversion to bioenergy, thereby reducing capital costs and scalability challenges while making a contribution to energy independence and national security.

Keywords: bioenergy; wastewater; biomass; biological engineering; renewable energy

1. Introduction

Bioenergy is renewable energy from biological sources, and biological carbon-based wastes have the potential to provide significant renewable energy for transportation and power needs, both in the United States (U.S.) and worldwide. Waste-based biomass includes waste from agriculture and forestry operations as well as biomass produced from the treatment of waste liquids, solids, and gases.

Global consumption of energy is projected to increase by 50% over the period from 2007 to 2035, from 495 quadrillion British Thermal Unit (Btu) to 739 Btu. The percentage of total consumption of the 24 countries combined that belong to the Organization of Co-operation and Development (OECD), including the U.S., will equal 38% in 2035, while the non-OECD countries will consume 62% [70]. With regard to the most popular transportation fuel, ethanol, in 2008 approximately 33% of production occurred in Asia, Europe, and Africa [18]. Biofuels, like ethanol, are produced from biomass, and in the most biomass-intensive scenario, energy from biomass may contribute up to approximately 50% of total energy demand in developing countries by 2050 [18]. The Intergovernmental Panel on Climate Change (IPCC) has established methods and information that can be used for estimating national inventories of greenhouse gas (GHG) emissions for sectors that include energy, industry, agriculture and forestry, as well as waste generation and treatment [33]. Clearly, energy consumption and demand will rise globally with time and will require the development and utilization of diverse sources of feedstocks and processes.

1.1. U.S. energy needs and sources

Between 2013 and 2040, U.S. energy consumption is projected to rise by 8.9% [86]. For the year 2013, renewable energy accounted for 8% of total energy sources for the U.S. with petroleum (36%), natural gas (27%), coal (18%), and nuclear power (8%) comprising the other energy sources for a total amount of 97.1 quadrillion Btu used [86]. "Consumption of marketed renewable energy increases by about 3.6 quadrillion Btu in the reference case, from 9.0 quadrillion Btu in 2013 to 12.5 quadrillion Btu in 2040, with most of the growth in the electric power sector. Hydropower, the largest category of renewable electricity generation in 2013, contributes little to the increase in renewable fuel consumption. Wind-powered generation, the second-largest category of renewable electricity generation in 2013, becomes the largest contributor in 2038 (including wind generation by utilities and end-users onsite). However, solar photovoltaics (6.8%/year), geothermal (5.5%/year), and biomass (3.1%/year) all increase at faster average annual rates than wind (2.4%/year), including all sectors" [86]. Biofuels specifically include ethanol and biodiesel, while waste includes municipal solid waste from biogenic sources, landfill gas, sludge waste, agricultural byproducts, and other biomass [70]. The International Energy Agency (IEA) predicts biofuel's targets and mandates. They stated that Jamaica's renewable energy in transport is 11% (2012), 12.5% (2015), 20% (2030); Japan's is 500 million litres per year [Ml/y] (2015), 800 Ml/y (2018); Thailand's is 3 Ml/day ethanol, 5% biodesel blend (2011), 9 Ml/d ethanol (2017); United States is 48 billion litres (Bl) of which 0.02 Bl cellulosic-ethanol (2015), 136 billion litres, of which 60 Bl cellulosic-ethanol (2022); Vietnam's is 50 Ml biodesel and 500 Ml ethanol (2020) [87]. Biofuels are projected to have the largest increase in meeting domestic energy consumption, growing from 3.5% to more than 11% of liquid fuels by 2035 [70].

Transportation fuels and power production are two major sectors where renewable bioenergy from waste-based biomass could significantly improve energy independence and security. The transportation sector uses more than 71% of the oil consumed in the U.S. Approximately 8.1 million barrels of oil are required per day to fuel 232 million vehicles that constitute the U.S. light-duty transportation fleet [88]. The Energy Independence and Security Act of 2007 (EISA) set goals to reduce dependence on fossil fuels and greenhouse gas (GHG) emissions from the transportation sector in the U.S. by increasing the supply of renewable transportation fuels, including advanced and cellulosic biofuels and biomass-based diesel, to 36 billion gallons by 2022 [88].

Total U.S. energy consumption is projected to grow at a modest rate, averaging 0.3%/year from 2013 through 2040 (86). Dry natural gas production remains the largest contributor to total U.S. energy production through 2040. Coal's share of total U.S. energy production is predicted to remain slightly above 20% of total U.S. energy production through 2040. A marginal decrease in energy consumption in the transportation sector contrasts with growth in most other sectors. Declines in energy consumption tend to result from the adoption of more energy-efficient technologies and existing policies that promote increased energy efficiency [86].

Dedicated utility-scale biomass power applications offer a potential route to reducing reliance on fossil fuels and improving the sustainability of power generation. A near-term opportunity to increase the use of biomass for power generation, thereby reducing greenhouse gas emissions, could be realized by increasing the deployment of co-firing applications for biomass and biomass-derived intermediates in existing power generating facilities [33,69]. Renewable energy, including biopower, is projected to experience the largest increase in production capacity between 2008 and 2035 [70].

The U.S. Department of Energy has stated that biomass is the only renewable resource that can supplant petroleum-based liquid transportation fuels in the near term. *The U.S. has more than one billion tons of sustainable biomass resources, enough to displace approximately 30% of the country's present petroleum consumption.* Bioenergy could provide fuel for cars, trucks, and jets; make chemicals; and produce power to supply the electric grid [67]. The 2005 report was updated in 2011 [68] and adds value to the 2005 report by including a county-by-county inventory of feedstocks, prices and available quantities for feedstocks, and a more rigorous treatment and modeling of resource sustainability. The National Academy of Sciences [50] completed an assessment of biomass for energy, and the estimates compare well with the U.S. Department of Energy (DOE) 2011 estimates. The two U.S. DOE reports of biomass together address waste resources from forestry and agriculture, but not from non-terrestrial (algal) resources that have significant potential to positively impact renewable resources.

1.2. Role of biomass as feedstock for energy production

The role of biomass (including waste-based biomass) in renewable energy production and consumption in the U.S., dating back to 1950, is shown in Table 1. Waste biomass includes municipal solid waste from biogenic sources, landfill gas, sludge waste, agricultural byproducts, and other biomass. Data through 2000 also includes non-renewable wastes composed of municipal solid waste from non-biogenic sources and tire-derived fuels [71]. Since 1990, there has been a sustained increase in the use of waste biomass contributing to energy production.

The role of biomass in renewable energy consumption in the transportation sector from 1990-2010 is shown in Table 2 [71]. Data are not available before 1981, and there are no data available concerning the use of waste biomass for the production of transportation fuels. Controversy currently exists concerning the amount of energy input required compared with the energy output related to corn ethanol. The data available indicate significant increases in fuel ethanol related to biomass-based renewable energy for the transportation sector.

Table 1. Biomass-based energy production and consumption (trillion Btu) [71].

Year	Energy	Waste Amount	% Waste
1950	1,562	NA*	NA
1960	1,320	NA	NA
1970	1,431	2	<1
1980	2,476	2	<1
1990	2,735	408	15
2000	3,006	511	17
2010	4,310	454	11

* NA = Not available

Table 2. Biomass-based renewable energy consumption for the transportation sector (trillion Btu) [71].

Year	Fuel Ethanol[1]	Biodiesel[2]	Total
1990	60	NA*	60
2000	135	NA	135
2010	1,070	28	1,098

[1] Fuel Ethanol has 3.553 million Btu per barrel
[2] Biodiesel has 5.259 million Btu per barrel

* NA = Not available

Table 3. Biomass-based renewable energy consumption for the electric power sector (trillion Btu) [71].

Year	Total	Waste Amount	% Waste
1950	5	NA	NA
1960	2	NA	NA
1970	4	2	50
1980	5	2	40
1990	317	188	59
2000	453	318	70
2010	440	252	57

Table 4. EISA targets for fuels for 2022 as part of the renewable fuel standard [20].

BioFuel Type	Million Cubic Meters (Billion Gallons)
Renewable fuel	121 (36)
Advanced Biofuel	79 (21)
Cellulosic Biofuel	60 (16)
Biomass-based Diesel[1]	4 (1)

[1] Target for 2012

The role of biomass, including waste biomass, in renewable energy consumption in the electric power sector from 1950–2010 is shown in Table 3 [71]. The data indicate a significant waste biomass contribution to electric power energy consumption since 1990, comprising 60-70% of total biomass used for electric power.

Since 2005, several legislative, regulatory, and policy efforts have strengthened the focus on increasing and accelerating biomass-related research, development, and demonstration projects. These activities include the Presidential Memorandum on Biofuels of 2009; the American Recovery and Reinvestment Act of 2009; the Food, Conservation, and Energy Act of 2008 [21]; the Energy Independence and Security Act (EISA) of 2007 [20]; and the Energy Policy Act of 2008 [69]. The combined legislation was aimed at accelerating biofuels production, deployment, and use; enhancing research and demonstration projects; commercializing large-scale biorefinery projects; and providing economic incentives for biofuels investments. However the rapid development of bioenergy production from biomass has been limited by challenges related to infrastructure, innovative technology, and costs associated with cultivation, harvesting, and processing biomass.

It is important to understand the terms *renewable biomass*, *renewable fuel*, and *renewable fuel standard* as defined by EISA [20] in the context of bioenergy from wastes. The term *renewable biomass* refers specifically to: (1) planted crops and crop residues, (2) planted trees and tree residues, (3) animal waste and animal byproducts, (4) forestlands (non-federal) as a source of slash and pre-commercial thinnings, (5) biomass removed for risk management in areas occupied by people, (6) algae, and (7) separated yard waste or food waste. *Renewable fuel* refers to fuel produced from renewable biomass, used to replace or reduce the quantity of fossil fuel present in transportation fuel. The *renewable fuel standard* as identified in the U.S. Energy Independence and Security Act of 2007 [20] requires 136 million cubic meters (36 billion gallons) of renewable fuel to be produced by 2022, with annual requirements for advanced biofuels, cellulosic biofuels, and biomass-based diesel [see Table 4]. Attaining the target levels of biofuels by 2022, especially for biodiesel production, will require significant investment and innovation regarding large-scale production and processing, especially for algae production and fractionation of lipids [53] and product extraction by applying transesterification either in situ or in the extracted lipids.

Advanced biofuel refers to a renewable fuel that has greenhouse gas emissions at least 50% less than baseline lifecycle greenhouse gas emissions from gasoline or diesel (whichever is being replaced by the renewable fuel) sold or distributed in 2005. Advanced biofuels may include: (1) ethanol from cellulose, hemicellulose, lignin, sugar, starch (other than corn starch), waste material (from crop residue, animal, food, and yard), (2) biomass-based diesel, (3) biogas including sewage waste treatment gas produced through conversion of organic matter from renewable biomass, and (4) butanol or other alcohols produced by converting renewable biomass organic matter [20].

The strategic goal of the U.S. DOE Biomass Program is to develop commercially viable biomass technologies to enable the production of biofuels nationwide and reduce dependence on oil through the creation of a new domestic bioenergy industry, thus supporting the EISA goal of 136 million cubic meters (36 billion gallons) per year of renewable transportation fuel by 2022 and increasing biopower's contribution to national renewable energy goals by increasing biopower generating capacity [69].

1.3. Lagoons and land treatment systems for waste-based biomass-to-bioenergy systems

Two waste-based biomass production systems that currently have large nationwide infrastructures include: (1) wastewater treatment systems for algae biomass, and (2) land application/treatment systems for non-food biomass.

2. Wastewater as a Waste Feedstock for Biomass

The U.S. DOE [69] has indicated that using existing infrastructure with a readily available feedstock lowers capital cost and associated risk for the bioenergy industry. *We suggest that using wastewater from municipalities and industries as a resource, and combining wastewater treatment with the production of biomass, would provide benefits to both industries.* Also, the existing wastewater treatment infrastructure could be used for waste-based biomass production in the relatively near future, thereby reducing capital costs and scalability challenges.

2.1. Wastewater as a resource

Wastewater is beginning to be viewed as a potential resource that can be exploited and used as a feedstock for bioenergy production and/or valuable products [8,9,37]. Wastewater production within the U.S. has been estimated at 0.4 cubic meters (100 gallons) per capita per day, producing 122 million cubic meters (32,345 million gallons) per day [1,2]. The U.S. has an estimated 21,594 Public Owned Treatment Works in operation that manage wastewater collection, treatment, and disposal [1].

Many biological processes carried out by microorganisms are not only used to treat wastewater, but also have the potential to recover energy and resources from the wastewater to produce heat, power, chemicals, and valuable products [10]. This energy recovery and resource utilization can displace the fuels required for thermal heating of wastewater treatment processes, enhance power reliability, and reduce greenhouse gas emissions [11,33]. Electricity requirements alone have been estimated at 25 billion kilowatt hours per year to operate these treatment facilities [3]. Approximately 4% of the electricity produced in the U.S. goes towards moving and treating water/wastewater [3]. Along with electricity utilization, wastewater treatment plants incur additional costs for chemicals used for treatment and disinfection. The U.S. wastewater infrastructure was reported to require between $13 and $21 billion, with annual operating and maintenance costs calculated at an additional $21.4 to $25.2 billion [4,5]. Therefore using biomass, a byproduct of biological wastewater treatment, to produce bioenergy at wastewater treatment facilities has the potential to reduce external power requirements while providing a sustainable and non-petroleum source of energy.

Domestic wastewater is typically considered to contain all of the inorganic salts and trace elements necessary for biological growth and activity. Sufficient nitrogen and phosphorus are also required, followed by carbon to ensure optimal process functionality [12,35]. Analysis of the molar ratio of carbon, nitrogen, and phosphorus (C:N:P) is necessary for both wastewater treatment and bioenergy applications. It has been reported that the optimal C:N:P ratio in anaerobic digestion reactors for converting wastewater to methane gas is 100: 2.5: 0.5, while for fermentation of hydrogen it is 100: 0.5: 0.1 [13,14].

In addition to domestic wastewaters, other wastewaters including those from animals, agriculture, food processing, and industry, including petroleum processing and oil and gas extraction industries, have potential as sources of biomass feedstocks for bioenergy production. Agricultural and food processing wastes are typically higher in concentrations of organic and inorganic chemicals than domestic wastewaters [16,37]. With regard to animal waste, with an estimated 90.8 million cows in the U.S. as of 2012, the average amount of waste is calculated at 4.54 million cubic meters per day [12,17]. The food processing industry produces substantial amounts of wastewater from more than 20,000 companies in the U.S. [18]. It is estimated that the average large food processing company produces about 1.4 billion liters of wastewater annually [19]. Therefore agricultural and food processing wastes show great potential for bioenergy production**;** however other industry-derived wastewaters may contain pollutants such as toxic metals, salts, and organic chemical toxins that may constrain the uses of waste-derived biomass [20]. The large volumes of wastewaters from both petroleum processing and oil and gas extraction processes offer near term opportunities for testing the cultivation of biomass and conversion of the biomass to bioenergy utilizing these fossil-fuel based wastewater sources.

The State of Utah Office of Energy Development is currently evaluating the cultivation of microalgae biomass utilizing oil and gas extraction water and the thermochemical conversion of the biomass to bio-crude using hydrothermal liquefaction (HTL) technology at Utah State University in collaboration with the University of Utah and Brigham Young University based on using the rotating algal biofilm reactor (RABR) technology developed for wastewater treatment and bioproducts production [15].

More information is needed about annual volumes and characterizations of industrial wastewaters for biomass cultivation before determinations can be made about their potential for large-scale biomass production and uses for a variety of bioproducts. This information is critically important for assessing wastewater streams as sources of biomass cultivation for bioenergy production.

2.2. Wastewater-based algae biomass

2.2.1. Algae biomass feedstock for bioenergy: current issues and challenges

The U.S. DOE [69] has indicated that the algae pathway will require significant research and development in areas of feedstock production, feedstock logistics, and conversion technologies. While development time will be lengthy, the potential to displace imported oil by using biofuels is significant [69]. Section 228 of the EISA [20] identified algal biomass as a feedstock for the production of biofuels. EISA requires identification of development challenges, regulatory or other barriers that hinder the use of algae as a resource, and recommendations on how to encourage and further its development as a viable transportation fuel.

The U.S. DOE has specifically recognized the potential synergy of wastewater treatment and biofuel/biomass production from algae, stating, “Inevitably, wastewater treatment and recycling must be incorporated with algae biofuel production.” [69,81]. Pittman et al. [53] reviewed the potential of algal biofuel production and concluded that, based on current technologies, algae cultivation for biofuels without the use of wastewater is unlikely to be economically viable or provide a positive energy return. Lundquist et al. [38] analyzed several different scenarios of algae-based wastewater treatment coupled with biofuel production and concluded that only those cases that emphasized wastewater treatment were able to produce cost-competitive biofuels. They concluded that the near-term outcome for large-scale algae biofuels production is not favorable without wastewater treatment as the primary goal.

Challenges for algae feedstocks include production or cultivation, logistics, conversion to bioproducts, and issues with scaling up and integration. In addition to research and development strategies that focus on algal genetics, strain development, and cultivation strategies as described by the U.S. DOE [69], mixed culture algae cultivation on wastewaters generated by municipalities and industries provides additional and potentially significant inputs for producing abundant, cost-effective, and sustainable algae biomass supplies [15].

Using wastewater to supply nutrients for algae cultivation is advantageous for large-scale algae biomass production. Micronutrients required in trace amounts that are readily supplied include silica, calcium, magnesium, potassium, iron, manganese, sulfur, zinc, copper, and cobalt [36]. Macronutrients include nitrogen, phosphorus, and inorganic carbon, which are present in wastewater in milligrams per liter levels, with concentrations dependent on wastewater source [15]. For algae growth in wastewater, a standard C:N:P ratio used is 106: 16: 1 [5,15]. Therefore nutrients in wastewaters can offset the cost of commercial fertilizers otherwise needed for algae cultivation. Also, wastewater treatment revenues can offset algae cultivation costs.

Wastewaters, especially from industrial sources, may contain toxic organic chemicals and toxic ions that can limit the growth of algae [61]. High levels of ammonia, copper, salinity, and herbicides can inhibit or prevent the cultivation of algae biomass, therefore the wastewater should be characterized or tested in order to ensure that it is capable of supporting the growth of algae biomass.

Table 5 illustrates potential biomass productions for several types of wastewater resulting from municipal and industrial processes. Harvesting the biomass and converting it to bioproducts are addressed in subsequent sections of this publication. The information in Table 5 indicates significant potential wastewater-based algae biomass production from the sources identified.

Challenges with large-scale production of large quantities of algae biomass using wastewater include the following: recycling algal nutrients released during anaerobic digestion to increase the concentration of macronutrients, thereby increasing algae productivity; gas transfer and exchange; photosynthetically active radiation (PAR) delivery; environmental control; land and water availability; and harvesting; and processing. To prevent excess nitrogen or phosphorus from limiting algae cultivation, the molar ratio of the wastewater supply must match the stoichiometric ratio of the algae biomass. A common N:P ratio often used for average algae biomass is the Redfield ratio of 16:1 [60], however the specific ratio for a given wastewater may vary from 8 to 45 [35], and the ratios for the wastewaters shown in Table 5 vary from 5 to 338. Therefore nutrient management requires an assessment of the algae and wastewater stoichiometric ratios of N:P to determine whether one element is limiting the amount of biomass that can be cultivated. If so, the potential for blending additional wastes to achieve a ratio matching the requirements for algae biomass must be explored.

Algae can directly utilize carbon dioxide and often bicarbonate, but generally not carbonate [36,56]. Oxygen concentrations above saturation begin to inhibit photosynthesis, and this byproduct must be removed in order to prevent photooxidative damage. For open wastewater reactors that include raceways, rotating biological contactors, and trickling filters [52,85]; oxygen is readily removed from water to the atmosphere. However in closed reactors, oxygen removal is considered one of the most difficult challenges to overcome [12].

Table 5. Algae biomass potential from municipal and industrial wastewaters[1] (modified from [15]).

Waste Source	N (mM)	P (mM)	N:P (ratio)	Conc. (g/L)	Vol. (ML/Yr)	Biomass (kg/yr)
Distillery	193	22	9	42.8		
Swine feedlot	174	10	17	37.1		
Poultry feedlot	57	1.6	36	5.7		
Dairy	13	0.97	13	2.9	$2x10^{11}$	$5.8x10^{8}$
Tannery	20	0.68	29	2.4		
Winery		7.9	1.7	5	1.7	
Strong	Domestic	7.1	0.48	15	1.4	
Textile		6.4	0.58	11	1.4	
Coffee production	6.1	1.2	5	1.3		
Beef cattle feedlot	4.5	0.45	10	1.0		
Medium domestic	2.9	0.26	11	0.6	$1.2x10^{11}$	$2.7x10^{4}$
Weak domestic	1.4	0.13	11	0.3		
Coke plant	54	0.16	338	0.1		
Paper mill	0.79	0.02	40	0.1		
Food (average)	-	-	-		$1.4x10^{3}$	

[1] Information relevant to U.S

With regard to PAR, full sunlight at intensities of 2,000 microeinsteins per m^2 per sec or greater can cause photoinhibition and photooxidation of algal cells, resulting in cell damage [51]. Full sunlight intensities commonly occur in lagoons and ponds used to treat wastewater in the west, southwest, and southeast U.S. Conversely, algae beneath the surface are often light-limited (photodeprivation) [10].

Algae growth results in a general increase in pH value that can reduce the bioavailability of all three macronutrients, including phosphorus, nitrogen, and inorganic carbon. At pH values above 9.5, precipitation of phosphate as calcium phosphate prevents it being used for growth. High pH values cause a shift in nitrogen from ammonium to ammonia gas that exchanges from the wastewater into the atmosphere, and therefore the nitrogen is not bioavailable to the algae. An increase in pH can also shift inorganic carbon equilibrium from carbonic acid and bicarbonate forms, which are bioavailable, to carbonate, a form that is considered non-bioavailable to algae [36,56].

With regard to land and water availability, Sheehan et al. [58] concluded that, at least in the U.S., land is definitely not a limitation, and although the technology faces many research and development hurdles, resource limitation is not a valid argument against further development. According to the U.S. Environmental Protection Agency, there are more than 7,000 facultative lagoon systems in the U.S. treating domestic wastes [74]. Facultative lagoons have an aerobic zone on the top and an anaerobic zone on the bottom and are inhabited by facultative bacteria that can thrive in both aerobic and anaerobic environments. From the perspective of algae production, lagoon treatment facilities provide the combined benefits of land, water, and nutrient availability, with reduced need for preliminary site construction and infrastructure development. For these reasons, lagoons are promising potential algae production facilities. One facility is the Logan Regional Wastewater Treatment Plant, located in northern Utah. The plant has 186 hectares (460 acres) of lagoons, and the facility managers are evaluating an algae-based approach to wastewater treatment with additional production of bioproducts [26].

Separating microalgae from water represents an estimated 20-30% of the total expense of producing algae biomass [45]. Most wastewater treatment plants in the U.S. do not harvest algae [57]. Those that do generally use dissolved air flotation or sedimentation preceded by chemical coagulation [23,62]. Although effective at full scale, the addition of chemical coagulants transforms a potential resource into waste sludge that must be disposed of [32]. Lowering the cost of harvesting algae and harvesting in a way that allows for the creation of bioproducts remains a challenge [15].

Therefore, although there is significant potential for the utilization of algae biofuels, significant challenges and research and development activities are required for field scale designs, operations, and monitoring in order to achieve the potential of the technology, i.e., algal-based biofuels at industrial scale. In order to make algae-based fuel cost competitive with petroleum, improvements in algae culturing, harvesting, and processing must be achieved that are sustainable and cost effective at high volumes of algae-based biomass. Pittman et al., [53] observed in 2011 that based on technologies available at that time algal cultivation for biofuel production alone was unlikely to be economically viable or provide a positive energy return. The authors recommended dual-use microalgae cultivation for wastewater treatment coupled with biofuel production as a better option. As of 2016, there is still a need to integrate these industries, which will be required as part of the strategy to make algae-based fuels cost competitive with petroleum. In addition, there is a need to include bio-crude produced from hydrothermal liquefaction of waste-cultivated algae-based biomass as part of the strategy to make algae-based fuels cost competitive with petroleum."

2.2.2. Algae biomass feedstock for bioenergy: biomass production systems

For wastewater systems, algae grow as a mixed culture as suspensions and as biofilms. For suspended cultures, the most common are referred to as raceways or high-rate algal ponds (HRAPs). Raceways use a paddle wheel to mix algae and nutrients, and to maintain algae in suspension for exposure to sunlight. Raceways are relatively inexpensive to build and operate, but often suffer low productivity due to contamination, poor mixing, dark zones, and inefficient use of carbon dioxide [14,39]. Raceway ponds should theoretically have production levels of 50–60 g per m^2 per day, and single day productivities at this level have been reported [58], but in practice, productivities of even 10–20 g per m^2 day are difficult to achieve consistently [59]. A major conclusion of cost-analysis studies conducted by the U.S. Department of Energy's Aquatic Species Program is that there is little prospect for any alternatives to the open pond system, given the requirements for producing low-cost fuels [58].

The use of algal biofilms could play a large role in overcoming the major challenges to production and harvesting of microalgae. The wastewater treatment industry is already accustomed to large scale biofilm processes [84], and according to Middlebrooks et al. [44], if enough surface area is provided, algae biofilm growth can be greater than suspended growth. A scalable algal biofilm system could be integrated into the treatment process, thereby achieving the dual benefits of inexpensive nutrient supply and treated water. Surface attached algal biofilms can offer the same increased culture density, and also lower land and water requirements of matrix-immobilized cultures [64,66] without the associated costs of the matrix. In the wastewater treatment field, bacterial biofilm-based reactors, including trickling filters and rotating biological contactors, have been used successfully at large scales [84]. Compared to suspended cultures, an algal biofilm system can better integrate production, harvesting, and dewatering operations, potentially leading to a more streamlined process with reduced downstream processing costs [15].

Two recent biofilm-based technologies include the Algal Turf Scrubber and the Rotating Algal Biofilm Reactor (RABR). The Algal Turf Scrubber consists of a plastic mesh for filamentous algae attachment with intermittent wave surges. It has been reported to have a biomass production of 15–27 g per m^2 per day [1]. Several other studies with this design have shown good nutrient uptake and biomass productivity that typically ranges from 5 to 20 g per m^2 per day [47,48,82]. However the filamentous algae grown on the Algal Turf Scrubber have low fatty acid content, reducing its value as a biofuel feedstock [49].

The RABR is designed to operate in the photoautotrophic conditions of open tertiary wastewater treatment, producing mixed-culture biofilms made up of algae and bacteria. Using a cotton rope substratum, the RABR at pilot scale (8,000 L) achieved effective nutrient reduction, with average removal rates of 2.1 and 14.1 g per day per RABR for total dissolved phosphorus and total dissolved nitrogen, respectively. Biomass production was 31 g per day per RABR. The biofilm removed from the substratum contained 12–16% solids, which is equivalent to or greater than solids concentration achieved by centrifugation, tangential filtration, gravity sedimentation, and dissolved air flotation [15]. In addition, a spool harvesting technique was developed to recover the biofilm at 12–16% solids that was suitable for further processing for biofuels and bioproducts [15].

2.2.3. Algae harvesting and processing

Logistics involve developing and optimizing cost-effective integrated systems for harvesting, collecting, storing, preprocessing, handling, and transporting algae. In the case of algal feedstocks, there is also a focus on developing effective ways to process or fractionate algae biomass directly into different fuel or product precursors [69]. With regard to conversion to bioproducts after cultivation and harvesting of algal feedstocks, algal biomass may require processing or fractionation into lipids, carbohydrates, and/or proteins before these individual components can be converted or further processed into the desired fuel or product. Feedstock quality and conversion specifications for specific types of bioproducts need to be addressed. Current technologies for algal fractionation and product extraction are not commercially viable, scalable, or sustainable. Options to circumvent or improve these processes exist; for example, conversion of whole algal biomass or secretion or direct production of the desired fuel or product in culture can be used, but little data exist on the cost, sustainability, and efficiency of these processes [69]. Currently large-scale algae biomass conversion processes are being tested for production of bioproducts including bioacetone, biobutanol, and bioplastics at the Sustainable Waste-to-Bioproducts Engineering Center [22].

Finally, algal biomass production, harvesting, and processing scenarios will require techno-economic and life-cycle analyses to evaluate materials, energy, and economic costs and benefits in order to determine the potential national impact upon transportation and power supplies.

2.3. *Wastewater-based terrestrial biomass using land application*

Municipal wastewater and wastewater from industries such as food processing or beverage production can also be used to grow plants in terrestrial systems. These plants can be converted to biofuels, thus using the nutrients (nitrogen, phosphorus, potassium, and macro- and micronutrients) and abundant water content present in most wastewaters, while conserving groundwater resources. The nutrients and water allow the growth of biofuel crops on even barren, untilled, or marginally productive lands. The establishment of plants grown for biofuels in marginal or degraded lands may offer additional environmental benefits, such as protection from soil erosion and nutrient leaching, and improvement of soil properties [42]. For example, Del Porto [17] has estimated that wastewater from Reno and Las Vegas in Nevada could produce more than 10 million barrels of palm oil a year using barren desert lands.

Generally, secondary wastewater is used for biomass production in land treatment systems. This is wastewater that has been treated through biological degradation processes following primary treatment to remove solid particles that can clog irrigation systems. It still contains nutrients, but few particles.

Similar to the situation for the utilization of wastewaters, especially wastewater from industries, for the cultivation of algae biomass discussed in Section 2.2.1, the impact on terrestrial biomass of ammonia toxicity and other specific chemicals can be evaluated through the application of toxicity assays [61]. Characterization of a wastewater with regard to the suspected presence and concentration of herbicides should also be conducted.

In Arizona, which has a hot, arid environment, researchers at the University of Arizona [40] have suggested using treated wastewater to grow sweet sorghum, a crop that requires little water, has low nitrogen needs, and thrives in high heat. When juiced, sweet sorghum yields sugars instead of starch, thus eliminating the need to break starch into sugars during the conversion process to ethanol.

The Biofuels Center of North Carolina has several current projects utilizing wastewater and biosolids for production of biomass. The City of Raleigh, NC is producing biodiesel derived from sunflowers at the Neuse River Waste Water Treatment Plant, a 227,000 cubic meters per day (60 million gallons per day) facility. The City utilizes reclaimed wastewater and stabilized biosolids from the treatment plant for irrigation and fertilization of the sunflowers on 607 hectares (1,500 acres) of farmland owned by the City [63]. The sunflower seeds are crushed and processed into biodiesel, which fuels city buses, trucks, and tractors. The City is presently investigating the use of canola during winter months to continue biomass production through the colder season.

Current major biofuel production systems, i.e., monoculture crop and cellulosic ethanol biomass, are highly dependent on adequate nitrogen fertilization to produce a high yield of energy [27]; many wastewaters can provide this necessary nitrogen. Additional advantages of using wastewater to produce biomass include protecting receiving waters, promoting energy independence, minimizing fertilizer use, creating new cash crops for farmers, and substituting plant-derived fuels for petroleum-derived fuels [17]. Nitrogen fertilizers are often produced using fossil fuels, so reusing nitrogen present in wastes also serves as a means to reduce the use of petroleum-derived fertilizers.

An example of the use of wastewaters for production of biofuel biomass is in Sweden, where commercial use and treatment of wastes has been accomplished using short rotation willow (*Salix* ssp) plantations for the production of biomass [31]. Short rotation plantations are non-food/non-fodder forestry land-use systems where fast-growing tree species such as willows or poplars are managed in short coppicing cycles. Coppicing involves repetitive felling of the same tree stump, near to ground level, and allowing the shoots to regrow from that main stump. The intensity of cultivation, the high nutrient uptake, and the frequent harvests require constant irrigation and fertilization, which can be supplied by irrigating with nutrient–rich wastewater. The shoots, which are usually harvested every two to eight years, can be used as a renewable fuel for heat and power or processed into liquid biofuels.

In Sweden, wood chips produced from willows are used as energy sources. Most large district heating plants in Sweden are built so that wet wood materials can be combusted. Willows, due to their relatively large leaf area, require large amounts of water for optimum growth [29]. Using wastes to irrigate willows saves natural water resources. Wastes that are applied to or treated using willow plantations in Sweden include sewage sludge (biosolids), landfill leachate, and municipal wastewater.

Almost ten percent of biosolids from treatment plants (corresponding to about 100,000 tons of dewatered biosolids with about 20% dry solid content) in Sweden are used for fertilization of willow plantations [2]. Biosolids may contain relatively high amounts of phosphorus due to phosphorus removal methods used in the treatment of wastewater that result in concentrating in the biosolids the phosphorus removed from the wastewater, thus requiring nitrogen and potassium to be supplied from other sources [30].

Wastewater from some 10 Swedish treatment plants is treated in willow plantations rather than in conventional treatment unit processes. Wastewater effluent can supply nitrogen, phosphorus, potassium, and various macro- and micronutrients. Another advantage of growing willows is the resulting accumulation of carbon in the soil through the capture of carbon dioxide from the atmosphere via photosynthesis [8]. Willows also produce less carbon dioxide through respiration than traditional agricultural crops such as rape and cereals [9].

Wood chip annual production from a well-established plantation of willow coppice with shoots four to six meters high ranges from 10 to 15 tonnes of dry matter per acre [31], which is an energy equivalence of four to six tonnes of oil per hectare. Approximately 15,000 cuttings can be established per hectare; after three to four years, the first harvest is taken. Three to five year-old shoots are harvested, with six to eight harvests during the 25 to 30-year productive life of the coppice.

Arundo donax (Adx), a non-food crop commonly known as giant reed, is another potential biomass plant for production of biofuels (ethanol or combined heat and power generation). In Australia Adx, when grown on saline land and irrigated with saline winery wastewater during a drought year, produced high biomass yields—45.2 tons per hectare per year of oven dry tops [83]. Adx can also be used for carbon sequestration. During the first year of the Australian study, Adx accumulated 20.6 tons of organic carbon per hectare in the dry tops of the rootstock. Adx removed large quantities of nutrients (528 kilograms per hectare of nitrogen, 22 kilograms per hectare of phosphorus, and 664 kilograms per hectare of potassium) from the applied wastewaters, thus reducing their loading into riparian or groundwater systems.

Chatzaki et al. [13] conducted a study in Greece to evaluate biomass production of castor bean (*Ricinus communis* L.) using irrigation water from the biological treatment unit of the city of Iraklion. Castor bean is a potential non-edible oil crop due to its high potential for annual seed production and its tolerance for diverse environmental conditions. Castor bean can be grown on marginal lands that are usually unsuitable for food crops. Results suggested that wastewater effluent could constitute an important source of irrigation water and nutrients for biofuel crop cultivations with minor adverse impacts on soil properties and seed yield.

A concern associated with the use of wastewater, especially in arid areas with high evapotranspiration rates and low humidity, is the possible accumulation of salts in the soil to toxic levels, especially sodium chloride. A means of remediating this problem is to use excretive halophytes, which are plants that transport sodium and chloride ions to the leaves, where they are excreted as a solid. Harvesting leaves from these plants on salt-affected soils will remove the salt from the soil. Examples of salt-excreting plants include saltwater cord grass (*Spartina*), salt bush (*Atriplex*), salt cedar (*Tamaris L.*), saltwort (*Salicornia spp*), and Russian thistle (*Salsola spp*) [17]. These ion-excreting plants can be chipped and used as a biofuel.

High sodium content of a wastewater may also result in a decrease in water infiltration rates such that sufficient water cannot supplied to the plants for good growth due to deterioration of physical condition of a soil, including formation of crusts, waterlogging, and reduced soil permeability.

Specific ion toxicity to crops must also be considered. The ions of most concern are sodium, chloride, and boron, which are present in household detergents and in industrial discharges. If the wastewater is chlorinated, the effects are chlorine residuals may be significant. In general, chlorine residuals less than 1 mg/L do not affect plant foliage while chlorine residuals greater than 5 mg/L can cause severe plant damage when sprayed directly on foliage.

Another problem that can occur with the use of wastewater is clogging of sprinkler and drip irrigation systems, especially with oxidation pond effluent due to biological growth (slimes), algae, and suspended solids. Most clogging occurs in drip irrigation, although drip systems are best for protection of public health, minimizing worker exposure to reclaimed water or spray drift.

However, there are methods used in land application systems to overcome problems with contaminants present in wastewater. Use of an assimilative approach to development of loading rates and loading frequency, whereby contaminants are applied to a soil at levels that will not cause adverse effects, can be used to ensure a well-functioning soil/biomass system.

3. Products Produced from Biomass Feedstocks

Biomass can be used to produce several different types of energy, including electricity generation, heat supply for homes or industrial processes, and fuel for vehicles [75]. Biomass is one of the oldest forms of energy used by humans (i.e., wood burning for heat). Its use for bioenergy comes from energy stored by plants, animals or their wastes, that are then released in the form of heat, power, or chemicals capable of providing energy [61,78]. The conversion of biomass to energy includes many different types and sources of biomass, conversion options, end-use applications, and infrastructure requirements [24,76].

The conversion of biomass to bioenergy can be separated into two different categories: biological conversion and thermal conversion. The main difference between the two is that biological conversion gives single or specific products (i.e., biogas, ethanol) and thermal conversion gives multiple and often complex products. The biological conversion process normally requires hours or weeks, while thermal conversion is typically completed in seconds or minutes [75]. Biological conversions include fermentations and anaerobic digestion [65], while thermal conversions include combustion, gasification, pyrolysis, hydrogenation, and liquefaction [61,69], including hydrothermal liquefaction, which converts wet and dry biomass into bio-crude using heat, pressure, catalyst, and an anaerobic environment, and catalytic gasification for producing a variety of gases that can include hydrogen from dried biomass.

3.1. Heat and power

The most common products from the conversion of biomass to bioenergy are heat followed by power generation. Combustion is the most traditional conversion technology used for heat and electricity production from biomass. The net energy available from combusted biomass ranges from 8 MJ per kg to 20 MJ per kg. The biomass can be used in boilers, gas and steam turbines, and engines [15,61]. When used to produce electricity, waste heat is a by-product, which is common in any power generating system. The waste heat can come from the engine oil, water cooling systems, or exhaust. This waste heat can be recovered and used within a process known as combined heat and power systems (CHP) [24,76]. It is reported that use of a CHP system within wastewater treatment plants can offset most if not all of the power demand of the treatment plant, and the thermal energy can be used to meet digester heat loads and space heating needs [77]. As of June 2011, CHP systems located within the U.S. were in place at 133 sites in 30 states within wastewater treatment facilities and had a 437 megawatt capacity. Potential for further CHP systems is reported to be more than 400 megawatts of biogas-based electricity generating capacity and 38,000 MMBtu per day of thermal energy production [77]. If these systems were implemented and also established in industrial sectors with CHP potential, substantial amounts of heat and power could be supplied, offering cost savings, added bonuses of reduced emissions of greenhouse gases, and more power reliability to energy intensive industries and processes known to be major contributors to greenhouse gases [80].

Another process for electricity production is the use of microbial fuel cells (MFCs) that simultaneously treat wastewater while producing electricity. MFCs are bioreactors that use exoelectrogenic biofilms for electrochemical energy production [34]. Whereas combustion and CHP systems are common on a commercial scale, MFCs are an emerging technology. The power densities from industrial and domestic wastewater have been reported to be between 4 to 15 watts per cubic meter for MFCs [34]. Although MFCs show great potential, users of MFCs must overcome several issues, including reducing the capital costs, optimizing reactor design, and gaining a better understanding of the biology of the system to provide more complete predictions of system behavior.

3.2. Bioenergy chemicals

A variety of biofuels can be produced using biomass including biodiesel, bio-oil, butanol, ethanol, hydrogen, methane, synthetic natural gas, and syngas [18]. The form of biofuel that is required often dictates the process route, followed by the available types and quantities of biomass [41].

Gaseous biofuels include hydrogen, methane, and syngas. Hydrogen (H_2) is a carbon-free renewable energy carrier, which can be produced through catalytic gasification, thermal, electro-chemical, or biological processes [69]. Biological hydrogen production can be accomplished by biophotolysis of water using microalgae, photodecomposition of organic compounds by photosynthetic bacteria, fermentative hydrogen production from organic compounds, or a combination of photosynthetic and fermentative bacteria in a two-stage process [4,43,79]. A major advantage of using hydrogen for energy is that its combustion does not release greenhouse gas emissions and results in pure water as a byproduct [16]. It also can be used in internal combustion engines with little modification to current gasoline engines. Advantages of hydrogen include rapid burning speed and high effective octane number, and it is flammable at a wider range of concentrations than is methane or gasoline [6].

Methane (CH_4), which is produced in combination with carbon dioxide (CO_2) from methanogenic archaea, is a product of anaerobic digestion [25]. Methane, which has a comparable calorific value to natural gas (35.8 versus 37.3 MJ/m^3), produces less carbon dioxide than other hydrocarbon fuels per unit of energy released and is capable of use in the current transportation infrastructure [25].

Synthetic natural gas is composed primarily of methane and is generated by processes such as catalytic hydrothermal gasification or anaerobic digestion [69].

Syngas, which can be produced during gasification by partial oxidation of biomass at high temperatures (800–1,000 °C), is a mixture of carbon monoxide (CO) and hydrogen (H_2) with other components such as carbon dioxide, methane, and higher hydrocarbons such as ethylene and ethane, propane, and propylene, and nitrogen from air gasification. Syngas can be burned directly or used as fuel for diesel or gas turbine engines and can provide the raw material for the production of almost every fuel and chemical used currently [11,54]. Both Syngas and synthetic natural gas can be further processed to fuels, chemical, and other liquid intermediates using biological or physico-chemical processes [69].

Liquid biofuels include biodiesel, bio-oil, butanol, and ethanol. Biodiesel is produced by a mono-alcoholic transesterification process where triglycerides react with mono-alcohols, commonly methanol or ethanol, through different process steps involving basic, acidic, and enzymatic catalysts [79]. Biodiesel has an energy content comparable to diesel, is renewable, biodegradable, reduces particulate emissions, and improves diesel engine lubricity [46,55]. Bio-oil, which comes mainly from pyrolysis amd hydrothermal liquefaction (HTL) is a dark brown viscous oil that contains organic acids, aldehydes, ketones, phenols, anhydrosugars, pyrolytic lignin, and water [7,69]. HTL is a thermochemical conversion process that can use wet biomass at high temperature, a catalyst, and an anaerobic environment to produce bio-crude, bio-char that contains phosphorus and gases, is performed at higher pressures and lower temperatures than pyrolysis, and is applicable for the conversion of algae biomass to bio-crude [69].

Pyrolysis is a process that converts biomass to liquid, solid, and gaseous fractions through heating in the absence of air at around 500 °C [41]. Combustion tests of bio-oils have shown efficient burning in standard or slightly modified burners. The water content, which is typically 25%, accounts for a low energy density, lower flame temperature compared to oils, and issues with ignition and preheating. Upgrading bio-oil is possible for direct use in vehicle engines [28].

Bioproducts including acetone, butanol, and ethanol have been produced from algae feedstocks in anaerobic reactors using anaerobic treatment of algae cultivated on wastewater [22]. Butanol, which is a product of acetone, butanol, and ethanol (ABE) fermentation, has an energy density of 29.2 MJ per liter and is comparable to gasoline [3,22,28]. Butanol has several advantages compared to ethanol, such as being less corrosive and having a lower vapor pressure. Also it does not absorb water, making it easily integrated into the current fuel infrastructure [19]. Ethanol, currently the most widely-used biofuel, is produced most commonly through anaerobic fermentation utilizing yeast [79]. In the U.S., ethanol is usually made from corn**.** In Brazil, it is most commonly made with sugarcane. Wheat, barley and potatoes are also sources of ethanol. Compared to gasoline, ethanol has a higher octane number, broader flammability limits, higher flame speeds, and higher heats of vaporization [5].

4. Summary

The potential for generating bioenergy from biomass cultured with wastewater is significant. The U.S. DOE has indicated that using existing infrastructure with a readily available feedstock lowers capital cost and associated risk for the bioenergy industry. Since 1990, there has been a sustained increase in the use of waste biomass for contributing to energy production. The U.S. produces daily wastewater volumes that include 121 million cubic meters (32 billion gallons) of domestic wastewater, 4.5 million cubic meters (1.2 billion gallons) of dairy waste, and approximately 3.8 cubic meters (1 billion gallons) of food processing industry waste. Therefore domestic, agricultural, and food processing wastewaters show great potential for conversion to biomass for bioenergy production through biological and thermal processes to supply transportation and electric power needs for the U.S., which strengthens the strategy for achieving a cleaner and more energy independent and secure country.

Near-term challenges for significantly increasing the contribution of waste-based biomass to bioenergy production include developing a collaborative and integrated system for wastewater-produced biomass, biomass harvesting, and biomass processing to bioenergy products. Such collaboration has not been demonstrated. The existing infrastructure for wastewater treatment facilities that include secondary wastewater treatment plants and land applications systems can be used for managed biomass production, resulting in reduced capital costs and scalability issues and providing a training ground for development of commercial-scale biomass production and conversion to bioenergy.

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Conflict of Interest

All authors declare no conflict of interest.

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