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Viability of Reclaiming Municipal Wastewater for Potential Microalgae-Based Biofuel Production in the U.S.

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Abstract: Reclaimed municipal wastewater is a crucial component in biofuel production, especially in regions experiencing increasing freshwater scarcity. However, accurately estimating the potential for fuel production is challenging because of the uneven distribution of biofuel feedstock regions and wastewater treatment plants (WWTPs). This study assesses the viability of using reclaimed municipal water for algal biomass production in pond systems co-located with WWTPs under scenarios driven by biomass production and based on water transport logistics. We performed state- and county-level analysis of reclaimed water resources throughout the United States based on WWTP facility data. We overlaid these data onto estimated algae facility sites and examined the temporal resource availability to address seasonal variations in cultivation demand. Our findings reveal that 2694 billion liters per year of reclaimed water could potentially be used to produce 42.2 million metric tons (ash-free dry weight) of algal biomass, equivalent to 29.2 billion liters of renewable diesel equivalent (RDe). The use of reclaimed water would double current national water reuse and expand such reuse significantly in 455 counties across the United States. However, when we limit the construction of algae facilities to counties that can fully meet their water demand in order to minimize water transport burdens, the available supply decreases by 80%, to 512 billion liters, resulting in annual production of 12.2 billion liters of RDe, which still doubles current biodiesel production. Our analysis highlights the degree to which the location and flow of WWTPs and water transport affect the deployment of algae biofuel facilities and tradeoffs. These findings underscore the importance of improving the current WWTP infrastructure for reclaimed water reuse, especially in southern states.

Keywords: municipal reclaimed water; renewable biodiesel; geospatial temporal analysis; water availability

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1. Introduction

Biofuels have gained significant traction as a renewable fuel aimed at reducing greenhouse gas (GHG) emissions and achieving zero fossil carbon use. The growing concern over global climate change—evidenced by the increasing intensity and frequency of extreme events, as well as prolonged droughts—has accelerated the development and deployment of biofuel technology. Because biofuel feedstock is predominantly plant-based, it requires water for growth. Water demand varies depending on the type of feedstock, soil conditions, and climate in the growing region. This demand for water can have a significant impact on the availability of regional freshwater resources, with varying degrees of impact depending on the richness of natural water resources in the area. The increased water demand may also affect water usage in other economic sectors within the region. A comprehensive analysis of the water resource component of bioenergy production is critical for the successful expansion of the bioenergy industry and the long-term viability of advanced bioenergy systems.

Acknowledging the limitations of freshwater resources, industries have begun to explore non-traditional water sources for their production processes. Reclaimed municipal wastewater is a key component in the production of biofuels, particularly in areas experiencing increasing stress on freshwater resources. Among the water-intensive biofuel feedstocks, algae show promise for their potential as a renewable biodiesel that is compatible with existing infrastructure. Extensive research has been conducted to assess the potential of algal biomass production and regional water sustainability implications [1–6]. Notably, Wigmosta et al. [6] found that growing algal biomass at 8.7 g m^{-2} d^{-1} productivity in an open pond would require a substantial amount of freshwater (1421 L per liter of oil on average). With a supply of waste carbon dioxide (CO_2) sources to increase cultivation productivity to 26 g m^{-2} d^{-1} and considering climate, land, and stream flow, Coleman et al. [5] identified 7075 potential algae pond sites across the United States. Davis et al. conducted a harmonization study that predicted that 104 million metric tons (MMT) of algal biomass (on an ash-free dry weight (AFDW) basis) can be produced from all freshwater sites on 2.7 million acres of suitable cultivation land across the southern contiguous United States [2]. These studies emphasize the influence of local climate and seasonal patterns on evaporative water loss in different regions, a finding echoed by Xu et al. [7]. The available fresh water for these sites is significantly reduced when researchers account for the surplus water needed to ensure wildlife ecosystem services during low-flow events [8]. Because of the significant overlap between regions suitable for algae production and those experiencing high water stress, a site selection strategy aimed at decreasing algae freshwater consumption by 62% would result in an average 25% reduction in biomass yield [9]. These findings underscore the importance of employing non-traditional water resources for algal biofuel production [10–12].

Venteris and colleagues [4] examined the availability of saline groundwater, seawater, and freshwater for use in open-pond algae cultivation systems. When using saline water and external CO_2 sources to support cultivation demand, their techno-economic analysis estimated an annual national-scale biomass potential of 235 MMT could be achieved, but that increased costs for salt handling and disposal [2] and tradeoffs among algae strain growth rate, site constructability, water availability, and infrastructure could constrain deployment [13]. Researchers also explored the potential of using produced water from hydraulic fractures [14] and petroleum refinery wastewater [15]. Davis et al. [16] modeled renewable diesel production from algae grown in a pond via hydrothermal liquefaction (HTL). That study found that three-season operation with a winter shutdown mitigated high GHG emissions, but the economics of that approach were hurt by underutilized equipment during slow-growth periods.

Growing algae in treated wastewater effluent can offer several benefits: providing nutrients, enhancing water treatment, recovering resources, and ensuring large water volumes available for reuse [17–21]. But researchers recognize that integrating wastewater treatment with algae production has both advantages and limitations. A techno-economic assessment by Clippinger and Davis [22] found that the revenues generated from treating wastewater outweighed all biomass production costs. They estimated a potential to produce 1135–1892 million liters of gasoline equivalent (MLGE) a year in the United States based on existing and projected future wastewater capacity flows. However, in a spatially explicit, high-resolution, life-cycle assessment (LCA), Roostaei and Zhang [23] identified land availability as the biggest obstacle to WWTP-centered algae production, a finding echoed by Dalrymple et al. [18]. Although algae photobioreactors integrated with WWTPs can achieve higher productivity [24], tradeoffs related to energy costs, production, and associated GHG emissions would constrain development.

One of the challenges in using reclaimed municipal water for algal biomass production is that the projected locations of algal pond facilities, based on climate requirements, rarely align with WWTP locations. WWTPs are typically located in or near densely populated areas with limited available land [18,21,23,25]. In addition, the requirements for algae growth restrict the application of algae pond systems to states with warm climates and exclude large urban areas (with high population densities) in colder climate regions. Furthermore, achieving high productivity in algae growth requires external CO_2 sources, adding another layer of geographical constraint. Techno-economic and life-cycle assessments have consistently emphasized that the location of an algae pond facility significantly impacts the economic feasibility of algal biofuel deployment [3,4,23,25–27]. The complexity of the interactions among these multiple factors underscores the importance of employing a systems approach to conduct a comprehensive assessment.

This study examines the viability of using reclaimed municipal water co-located with algae pond systems in various areas across the United States for biomass production. The primary objective is to estimate potential biomass production based on the available local reclaimed water and considering the associated challenges. This study estimates the potential for biomass production using a scale-down approach under three scenarios: considering the locations of both WWTPs and algae ponds driven by algae production, and based on concerns about water transport impacts. By incorporating varying geographic-scale analyses that emphasize water resources, this study aims to contribute to informed decision-making regarding the implementation of reclaimed water-based bioenergy.

2. Materials and Methods

2.1. Analysis Flow

The analysis incorporates geospatial and temporal factors by initially identifying the current locations and effluent volumes of publicly owned treatment works in the United States. Figure 1 illustrates the analytical process used for this study. We collected municipal reclaimed water data, including annual average municipal effluent from WWTPs across the country (in million gallons per day) from the Clean Watershed Needs Survey (CWNS) conducted by the United States Environmental Protection Agency (EPA) [28,29] in 2008 and 2012. The source data were classified by treatment level: primary treatment, secondary treatment, and advanced treatment. Primary treatment involves screening and chemical flocculation to remove particulates from the wastewater through sedimentation. Secondary treatment involves screening, chemical flocculation, biological oxidation through an activated sludge process, clarification to remove particulates and organic carbons, followed by disinfection before discharge to a water body. The advanced treatment scheme includes the processes listed for secondary treatment plus the removal of nitrogen and phosphorus. The annual reclaimed water flow value used in this study represents the sum of secondary and advanced treatment effluent from WWTPs. CWNS datasets categorize treated flow by the discharge method, (e.g., landscape irrigation, crop irrigation, pumping to industrial facility as cooling water, or discharge to groundwater as part of an ecosystem service program). WWTP effluent discharged to surface streams is considered available reclaimed water in this study. Because one county may contain multiple treatment facilities, the annual WWTP flow discharged to surface streams is summed at the county level across the United States for geospatial analysis. County-level WWTP annual effluent flows for 2008 and 2012 are available in Supporting Materials SI.

We overlaid the county-level reclaimed water flow, comparing it with the projected algae pond water demand. Because one county can potentially accommodate multiple algae pond facilities, we aggregated the water demands from algae facilities [5,6] to the county level for comparison. Supporting Materials SII provides the county-level algae pond areas, monthly biomass production rates, and water demand values for suitable land in southern U.S. states. The counties with both available reclaimed water flow and designated algae ponds are identified as production counties.

We examined the production counties more closely through temporal analysis, considering the variations in water demand from algae and the available flow of reclaimed water. We compared the monthly water demand from algae with the monthly available reclaimed water flow at each identified production county throughout the year. We calculated the variation in monthly effluent flow from the WWTP based on the average monthly percentage of annual flow from the literature [21]. A production county that can host an algae production site while providing, at minimum, four months of reclaimed water a year was identified as a qualified production county. We estimated the algae water demand that can be fully or partially met by available reclaimed water flow in the qualified production county using Equation (1). We used the results obtained from Equation (1) as input for the scenario analysis.

$$RWFA_{i,j} = \begin{cases} ARW, \ AWD > ARW \\ AWD, \ AWD \leq ARW \\ 0, \ AWD = 0 \end{cases} \Bigg|_{i,j} \tag{1}$$

$RWFA_{i,j}$—Reclaimed water for algae in month i, qualified production county j, volume;
$ARW_{i,j}$—Available reclaimed water in month i, qualified production county j, volume;
$AWD_{i,j}$—Algae water demand in month i, qualified production county j, volume;
i—month, 1–12, corresponding to Jan.–Dec.;
j—qualified algae production county;
Criteria for qualified production county: $i \geq 4$.

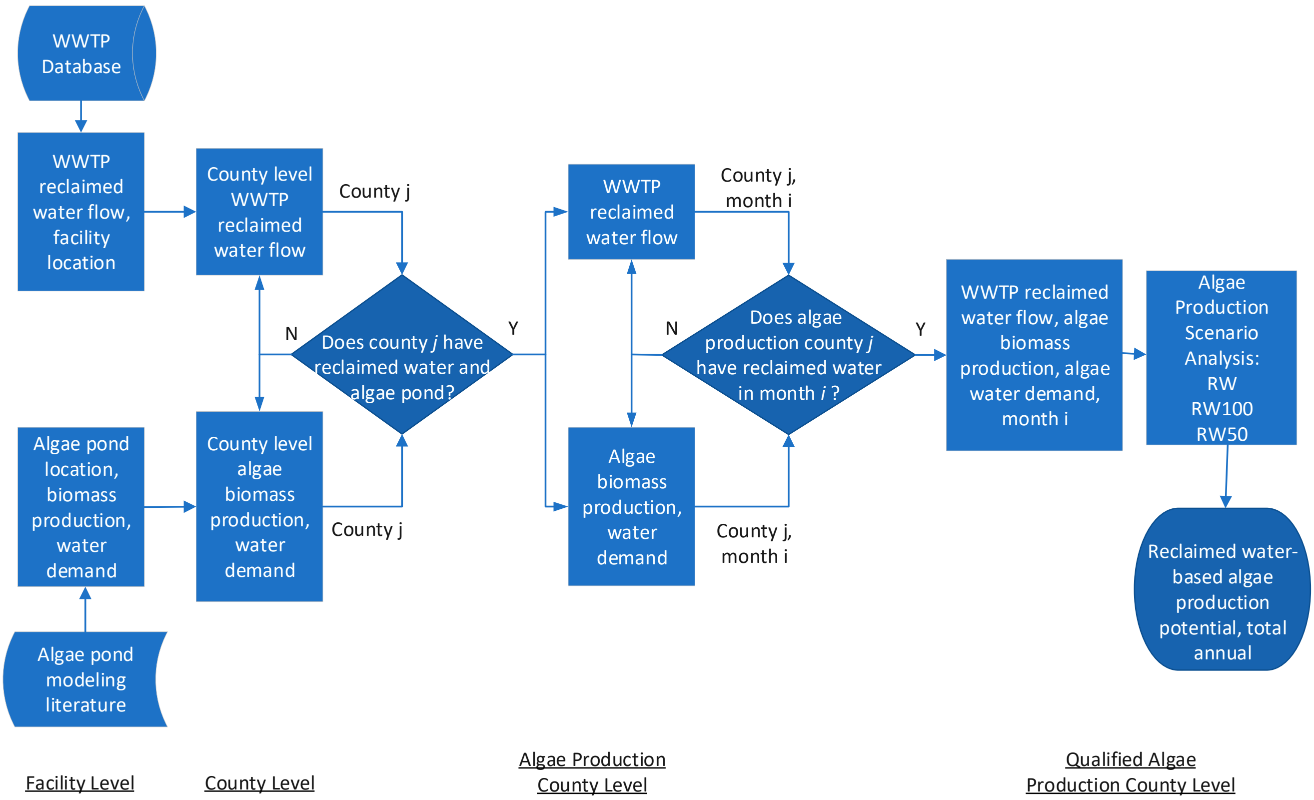

Figure 1. Schematic presentation of the analytical flow of this study.

2.2. Future Scenarios

We evaluated the use of municipal reclaimed water for algal biomass production in three scenarios: RW, RW50, and RW100 (Table 1). We further analyzed the reclaimed water for algae values (RWFAs) obtained from Equation (1) to estimate the reclaimed water volume used for algae production within the qualified production counties. The analysis involved comparing the total water demand for algae in each county with the available municipal reclaimed water in each scenario.

In the RW scenario, the focus is on maximizing production by using all the available reclaimed water resources in the qualified algae production county for algae cultivation for four or more months per year. Thus, the RWFA volumes under this scenario at each month for each county are essentially the same as the RWFAs calculated in Equation (1).

The RW100 scenario considers the current infrastructure limitations for reclaimed water. Most states examined lack dedicated purple pipelines for reclaimed water transport, which leaves trucking as the only viable choice. Unfortunately, this option would lead to a considerable increase in traffic within local communities, particularly during the high-growth season in summer. Moreover, transporting reclaimed water by truck could elevate the carbon intensity of algal biofuel due to GHG emissions, as evidenced by various life-cycle analyses and air pollutant emissions from diesel usage. The objective of this scenario is to reduce the burdens associated with water transportation by selecting algae production counties where the available volume of municipal reclaimed water can fully satisfy the water demands of all algae facilities within the county.

Table 1. Analysis scenarios.

Scenario	Water Source	Description
RW	Reclaimed water	Production-driven. Utilizes all available reclaimed water for production.
RW100	Reclaimed water	Production limited to counties that can fully meet water demand with reclaimed water to minimize water transport.
RW 50	Reclaimed water	Production reduced by 50% to reduce water transportation.
CW (Baseline)	Freshwater	Baseline water demand for algae production.

In the RW50 scenario, the volume of available reclaimed water meets at least 50% of the water demand observed in the RW scenario. This scenario represents the medium potential of reclaimed water use and production (between the RW and RW100 scenarios).

Equation (2) presents calculations for the RWFA under each scenario. Equation (3) calculates the algal biomass that can be produced when the algae water demand is met with the RWFA in each scenario. We compared the three future scenarios with a baseline (CW) scenario that illustrates the water demand for algae in the 7075 pond sites, as shown in Figure 2. We applied statistical analysis to the county-level results of the estimated available reclaimed water to determine the key metric (average, minimum, and maximum) values for the production states under the three scenarios.

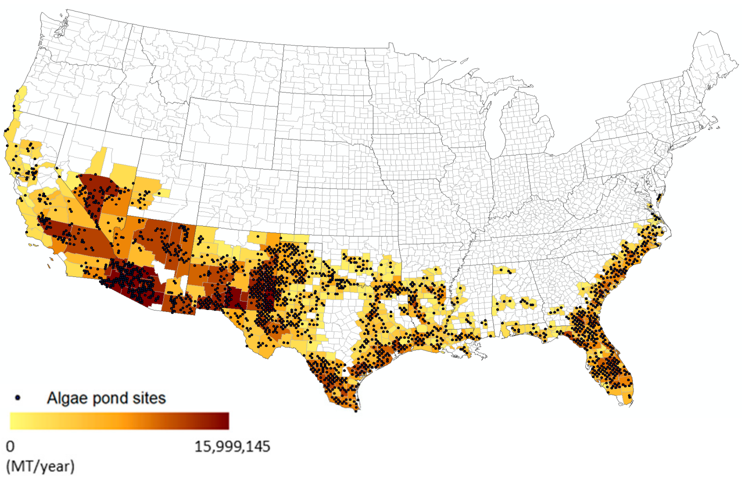

Figure 2. Estimated microalgal pond facility locations and potential microalgal biomass production. MT—metric ton. (Data source: [5]).

$$RWFA|_{i,j,RW} = RWFA|_{i,j}$$
$$RWFA|_{i,j,RW100} = \begin{cases} RWFA_{i,j}, \ RWFA_{i,j} \geq AWD_{i,j} \\ 0, \ RWFA_{i,j} < AWD_{i,j} \end{cases} \quad (2)$$
$$RWFA|_{i,j,RW50} = \begin{cases} RWFA_{i,j}, \ RWFA_{i,j} \geq 0.5 \times AWD_{i,j} \\ 0, \ RWFA_{i,j} < 0.5 \times AWD_{i,j} \end{cases}$$

$RWFA_{i,j,RW}$—Reclaimed water for algae in volume in month i, qualified algae production county j, under scenario *RW*;
$RWFA_{i,j,RW100}$—Reclaimed water for algae in volume in month i, qualified algae production county j, under scenario *RW100*;
$RWFA_{i,j,RW50}$—Reclaimed water for algae in volume in month i, qualified algae production county j, under scenario *RW50*.

$$Algae\ BM|_{i,j,k} = \frac{AWD_{i,j}}{ABM_{i,j}} \times \frac{1}{RWFA_{i,j,k}} \quad (3)$$

$Algae\ BM|_{i,j,k}$ —Algal biomass produced with available reclaimed water in month i, qualified algae production county j, under scenario k;
k—Scenarios, k = *RW*, *RW100*, or *RW50*;
$AWD_{i,j}$—Algae water demand in month i, qualified algae production county j, in volume;
$ABM_{i,j}$—Algal biomass production in month i qualified algae production county j if water demand is met, in mass units.

2.3. Algae Pond and Biomass Production

Projected algae pond locations and total production volume in the United States were obtained from two studies [5,6] that used an algae growth model coupled with a pond water temperature model to simulate a warm-season freshwater strain, Chlorella sorokiniana (DOE-1412), grown in open ponds measuring 100 or 200 m^2 (note that an algae production facility can comprise multiple ponds).

Those works considered climate (solar energy intensity and transmission, radiation), conversion efficiency, land suitability, and water resources for each site in the United States. Simulated biomass productivity averaged $\geq$20 g m^{-2} d^{-1} but varied with pond location. The pond temperature model simulated the temperature and evaporative water loss at the pond facility scale. A 5%-of-mean annual flow constraint was used to assess the total available freshwater supply for potential algal production sites. The water demand was calculated as the precipitation minus the evaporative loss. Biomass was harvested when the algae density reached 500 mg L^{-1}. Because the algae growth rate is greatly enhanced by adding CO_2, the studies screened the algae pond facilities within the contiguous United States for available external CO_2 supply sources, resulting in 7075 microalgae production facility sites. These data represent a baseline of freshwater demand for algae in our study (Figure 2). The algae pond locations and monthly water-use data are available in Supporting Materials SII.

Harvested algal biomass is converted into renewable biodiesel via hydrothermal liquefaction using the most current estimates of conversion yield [1–3], where approximately 67% of the carbon is converted into renewable biodiesel and 33% into naphtha. We used a conversion factor of 0.042 kg AFDW biomass per mega joule (MJ) of renewable diesel equivalent (RDe) (or 130.3 MJ gallon-1 of RDe at a lower heating value). The conversion factor was used to estimate the potential fuel volume produced from the reclaimed water-grown algal biomass.

3. Results

3.1. Geospatial Municipal Reclaimed Water Resource Availability

Reclaimed water generated from municipal wastewater treatment is the most abundant non-traditional water resource. Nationwide, 95–102 billion liters (BL) of municipal wastewater is treated each day; 38% of this water undergoes secondary treatment, and 62% is subject to tertiary or advanced treatment [28,29]. This resource is aggregated in urban and suburban areas (Figure 3). Of the total treated wastewater, approximately 9.5% is discharged to the ocean and 9.8% is applied for irrigation, industrial use, plant use, groundwater recharge, deep well injection, potable water, land application, and other uses. A substantial amount of the effluent (80%) is discharged to surface streams, and therefore, is available for further use.

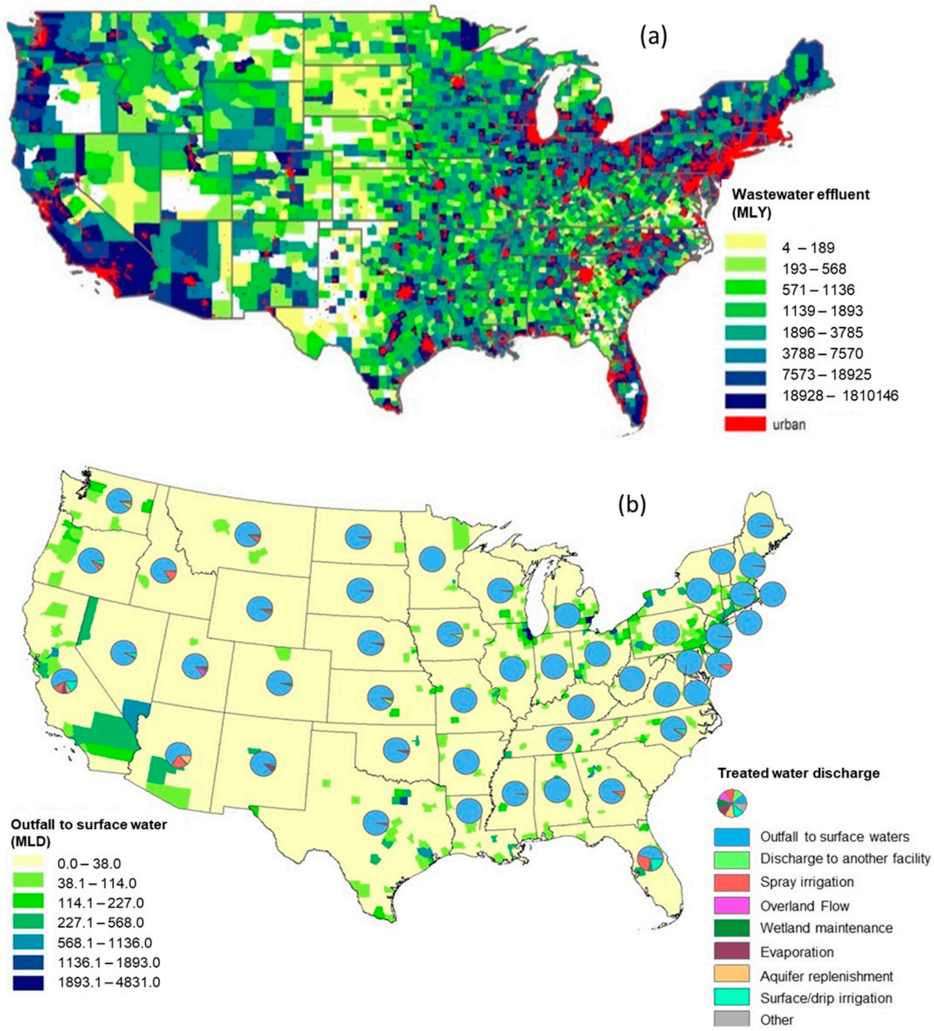

Figure 3. Geographic distribution of reclaimed municipal wastewater in the United States. (**a**) County-level wastewater effluent; (**b**) reclaimed water reuse breakdown. Background shades indicate the volume of reclaimed water discharged to surface streams; the pie charts show the fate of reclaimed water in each state (presented as a volume fraction).

Nationally, 5265 BL of municipal reclaimed water can be available annually in the states where algae can be grown in pond systems (Figure 4). The volume of available reclaimed municipal water varies significantly across states, from 2 to 800 BL in scenario RW. Annually, Texas and California have the highest available reclaimed water volumes in the projected regions. After satisfying the water demand for algae cultivation, our results indicate considerable volume for further water reuse in other economic sectors in Texas, followed by California, Louisiana, Arizona, and Oklahoma. Utah did not make the list because it does not have a reclaimed water source in the select pond locations.

Within an algae production state, available reclaimed water varies from county to county, as shown in Figure 5. Nevada leads all states with 100 BL of available reclaimed water a year on average, followed by California, Arizona, and Texas under the RW scenario. The top four states have large county-level variations. The degree of variations subsided under the RW100 scenario when the state average fell to below 5 BL. Texas remains the top candidate, offering an average of 21 BL of water per year. Some states can no longer provide reclaimed water to several sites in the RW100 scenario, including locations in South Carolina, Oregon, New Mexico, Nevada, Florida, and Arizona.

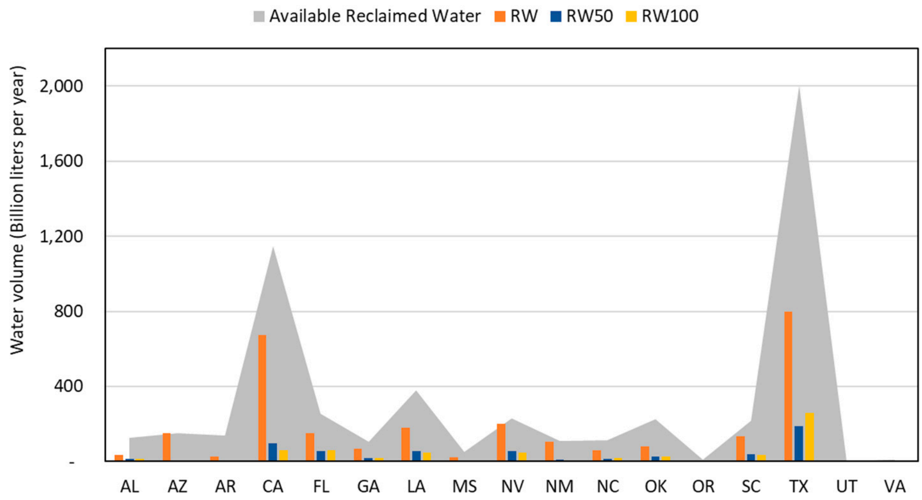

Figure 4. Annual total available reclaimed water in algae production states compared to algae water demand under the three scenarios. Virginia has a small demand that can be met by available reclaimed water (8 BL) (data not visible due to scale).

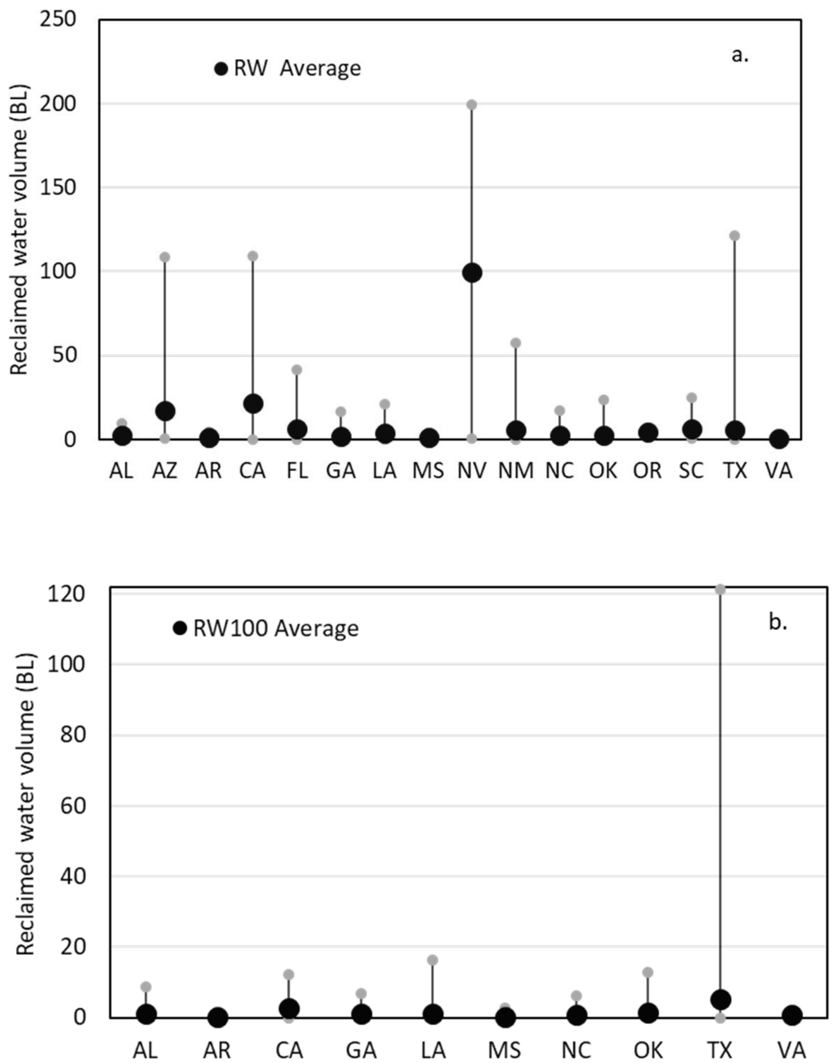

Figure 5. Maximum, minimum, and average of county-level annual available reclaimed water in the production states under scenarios (**a**) RW and (**b**) RW100. Black circle—average value, high grey circle—maximum value, and low grey circle—minimum value.

3.2. Temporal Reclaimed Water Availability

Municipal water treatment systems experience temporal variations that are influenced by weather conditions (e.g., surges in spring stormwater) and changes in domestic water use throughout the year. Figure 6 illustrates the monthly fluctuations in reclaimed water flow across 16 states. While these variations are subject to annual changes and are influenced by weather, the monthly fluctuations in most states are relatively minor compared to the fluctuations in algae water demand. The demand for algae water is determined by the seasonal productivity of algae cultivation. Typically, biomass growth increases in March and April, reaches its peak from July to September, and then gradually slows down. Figure 6 provides an example from a county in Texas (Federal Information Processing System (FIPS) code 48233, Hutchinson County), which is considered one of the regions with high algae water demand, to illustrate the stability of reclaimed water as a year-round resource. Moreover, if the water flow meets or exceeds the peak monthly water demand from algae production, it can be reliably used to support biomass production. The temporal screening selected qualified production counties for scenario analysis.

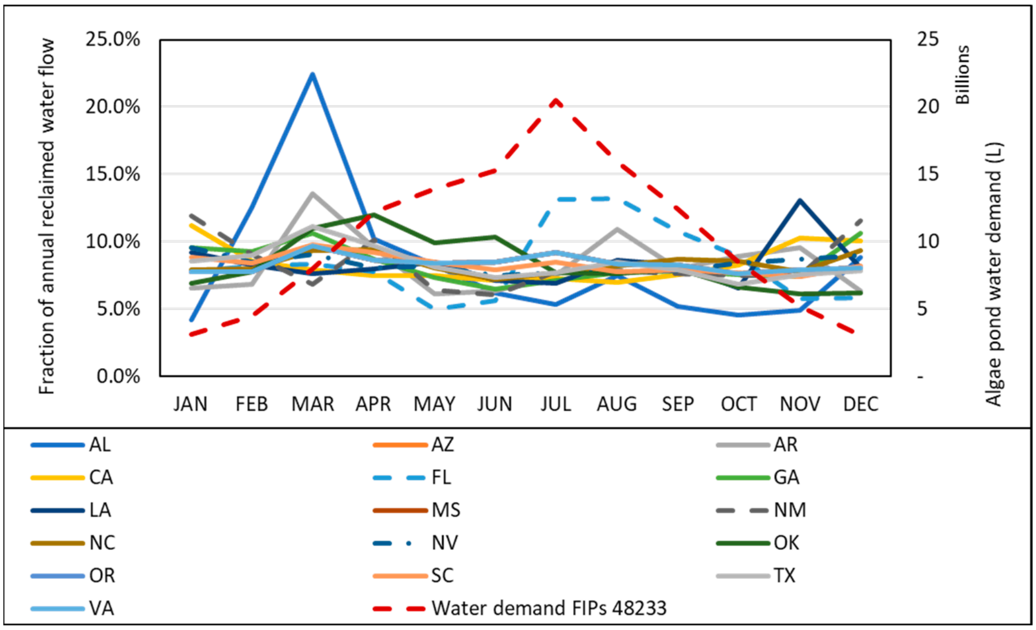

Figure 6. Monthly reclaimed water flow in algae production states. Note water demand for algae in Texas (FIPS 48233) (red dotted line) as an example of the fluctuations of the water demand.

In the United States, 3020 counties have municipal WWTP facilities, and 576 counties meet the qualifications for algae pond facilities based on cultivation and land assessments. After overlaying the two, we identified 458 production counties with both WWTPs and suitable sites for algae production. Considering the monthly flow of reclaimed water at the county level, a subset of 455 counties—qualified production counties—can provide water resources for at least four months each year to support production. In these counties, a total of 2694 BL of reclaimed water can be utilized under scenario RW. In scenario RW50, the available reclaimed water amounts to 584 BL, and in scenario RW100, it reaches 623 BL.

3.3. Total Reclaimed Water Resource for Production

Based on our estimates, scenarios RW, RW50, and RW100 could yield 42, 14, and 18 MMT of algal biomass, respectively, from the qualified algae production states using available reclaimed water in the 16 states, after considering the county-level monthly water demand. Figure 7 illustrates the algal biomass under these three reclaimed water scenarios in the algae production states. Texas is the top algal biomass-producing state in all three scenarios. Texas, Louisiana, Florida, and South Carolina offer the highest potential for biomass production under scenario RW. Together, these four states contribute three-quarters of the total biomass. Both Louisiana and Florida rank high in biomass production under scenario RW despite their relatively modest anticipated water resources (Figure 4). In comparison, while California can potentially access more reclaimed water (Figure 4), its production remains modest, likely because of the lower algae water utilization rate, which is influenced by the regional climate. Oregon is able to produce biomass in all three scenarios although the production level is low.

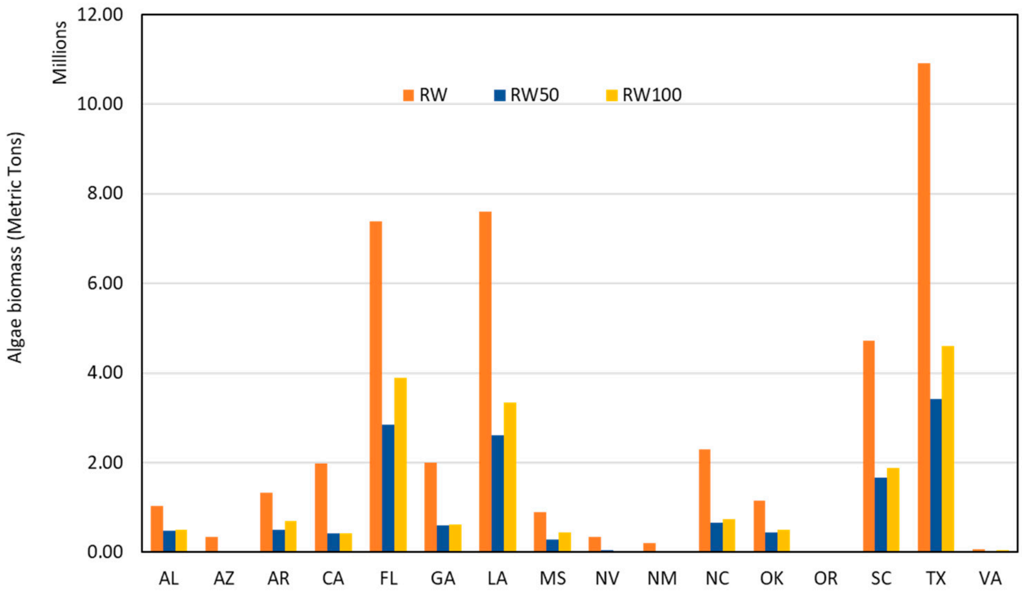

Figure 7. Biomass can be produced from reclaimed water in 16 southern states.

Under scenario RW100, where counties remain in production if their reclaimed water supply can fully meet the algae water demand, the numbers of production counties decline in most states. Interestingly, Texas can achieve a higher level of biomass production under RW100 compared to RW50 (Figure 7). Similar patterns were found in more than half of the states analyzed, indicating that a significant portion of algae facilities can obtain an adequate reclaimed water supply there. The results illustrate that if a county has a WWTP and algae pond facility, the algae water demand can be fully met in most cases. Biomass production values and reclaimed water-use statistics are available in Supporting Materials SII.

Figure 8 further illustrates the geospatial distribution of algal biomass production through the utilization of reclaimed municipal water across the southern states for the three scenarios. Out of the total 5265 BL per year of reclaimed water available in the potential algae production counties, the data indicate that 51% can support algae production in scenario RW. However, this utilization rate drops significantly to 11% under RW50 and to 12% under RW100.

As mentioned, 455 counties can provide water resources for scenario RW. When applying the criterion of meeting 100% water resource supply, the number of counties decreases to 264 (scenario RW100). Based on these results, the United States has the potential to produce an estimated 10–29 BL per year of RDe from algae based on current technology and using reclaimed water. Table 2 provides a summary of the reclaimed water volume used for algae, the number of counties supplying the reclaimed water, and the biomass and biofuel production potential under the three scenarios.

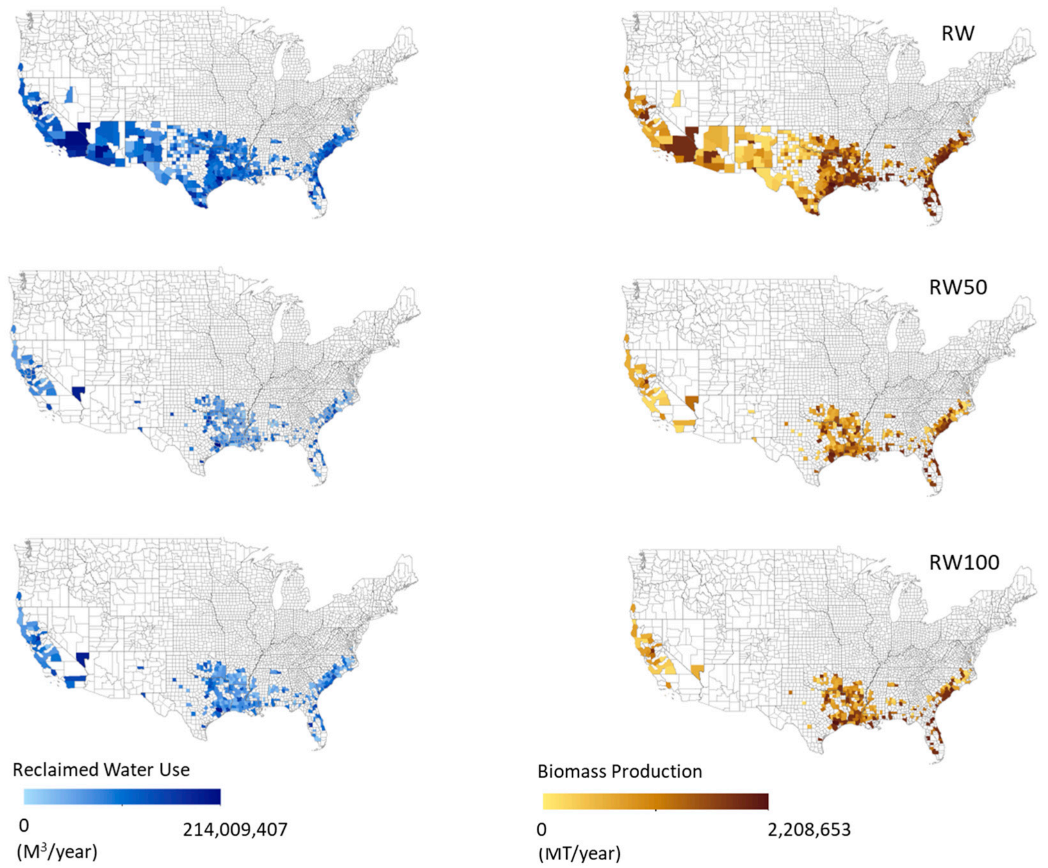

Figure 8. County-level reclaimed water supply and algal biomass production under three scenarios: RW, RW50, and RW100. The left panel presents available reclaimed water for algal biomass production; the right panel presents algal biomass production.

Table 2. Summary of reclaimed water supply for algal biomass production in three scenarios [1].

Scenario	Reclaimed Water Volume	Number of Counties	Algal Biomass	RDe via HTL
	(BL/year)		(MMT)	(BL/year)
RW	2694	455	42.2	29.1
RW50	584	290	14.0	9.8
RW100	612	264	17.7	12.2

Notes: [1] Harvested algal biomass is converted into RDe via HTL at a conversion rate of 0.042 kg AFDW biomass per MJ of RDe.

4. Discussion

4.1. Reclaimed Water-Use Efficiency

From a production perspective, an important metric for evaluating resource use is water-use efficiency (WUE), which measures the amount of biomass produced per unit of water. The same amount of water can result in varying amounts of algal biomass across different climate regions. WUE can help identify locations that achieve the most water-efficient biomass production.

When considering reclaimed water scenarios, the WUE is influenced by regional constraints and the availability of effluent water from individual WWTPs. Figure 9a,b presents the annual WUE of each state under each scenario, based on reclaimed water data (available in Supporting Materials SII). Out of the 16 states analyzed, 11 can produce at least 10,000 MT of biomass per BL of reclaimed water, on average. Utilizing reclaimed water for production tends to favor facility locations with higher WUE, with a few exceptions. Significant variations in WUE were observed among the three reclaimed water scenarios.

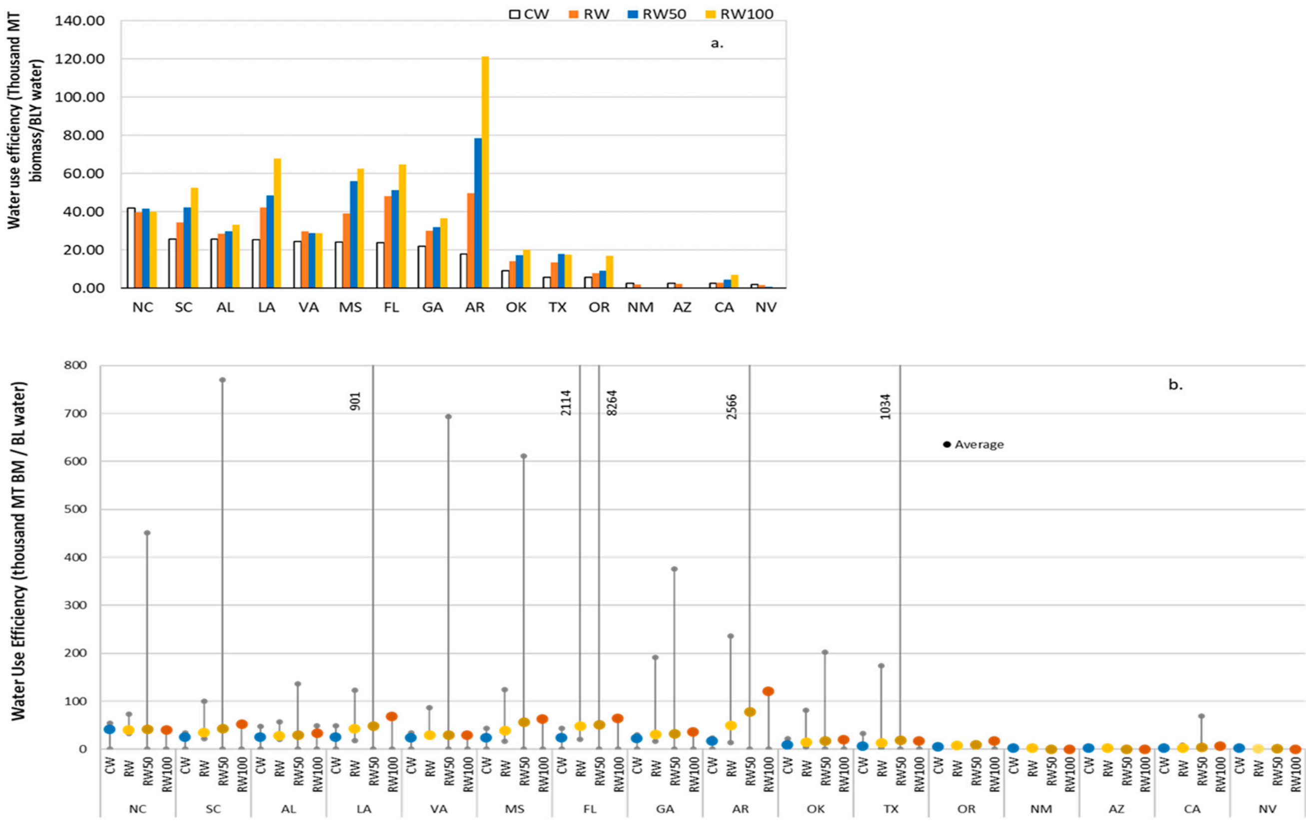

Figure 9. WUE for algae-producing states under the base assessment and three reclaimed water scenarios. (**a**) State weighted average of WUEs; (**b**) county-level maximum, minimum, and average WUEs. Data are available in Supporting Materials SII.

In scenario RW, the states with the most productive use of reclaimed water for biomass production are Arkansas and Florida, with WUEs ranging from 48,000 to 50,000 MT BL^{-1} (Figure 9a). They are followed by Louisiana, North Carolina, and Mississippi, which achieve WUEs of approximately 40,000 MT BL^{-1}. South Carolina, Virginia, Georgia, and Alabama show WUEs of around 28,000–35,000 MT BL^{-1}. The remaining states exhibit more modest WUEs, with all scenarios yielding less than 20,000 MT BL^{-1}.

It is important to note that in each scenario, the WUE at the county level also exhibits wide variations. Individual county WUEs can be significantly higher or lower than the state average, as shown in Texas, Arkansas, Florida, and Louisiana (Figure 9b). Those counties with high potential could be prime candidates for algal biomass production sites. These findings suggest opportunities for implementing operational schemes in certain counties to optimize biomass production with a low water footprint.

4.2. Scenario Comparison and Uncertainties

Scenario RW100 represents a near-term option where water demand from algae production facilities can be fully met by reclaimed water supply at the county level. The primary focus of this scenario is to reduce water delivery needs. This scenario concentrates the delivery requirements for the reclaimed water in just 264 counties—the lowest number among all three. It can provide an annual volume of 612 BL of reclaimed water (Table 2), resulting in 12 BL of RDe per year, effectively doubling current biodiesel production in the United States [30]. Compared to RW50, this scenario offers an additional 30 BL of reclaimed water, leading to a production increase of 3 MMT more biomass (equivalent to 2 BL more RDe) while impacting 30 fewer counties. The results show that RW100 can be a step towards large-scale co-location project development.

On the other hand, scenario RW represents the maximum biodiesel production potential by utilizing every drop of available reclaimed water for algae cultivation. The scenario presents up to 7.4 BL per day of reclaimed water use on average, effectively doubling nationwide water-reuse, and enabling the production of 29.2 BL per year of RDe, resulting in a four-fold increase in biodiesel production. However, a significant hurdle in this scenario lies in the involvement of many counties (455), leading to substantial water delivery requirements and their related impacts.

Our study highlights the abundant possibilities for resource-sustainable, algae-based biofuel production through co-locating an algae pond facility with WWTPs. However, it is essential to acknowledge that all modeling and analyses are inherently subject to uncertainties. The co-location of an algae pond facility with WWTPs brings about various operational, logistic, environmental, and economic challenges. In particular, the process economics of algae technology plays a crucial role in determining the feasibility of algal biofuel production. Additionally, the regulations concerning water reuse for algae pond application may vary from state to state, adding another layer of complexity. The lack of reclaimed water infrastructure and potential environmental and social impacts on local communities can significantly impact costs, reduce the availability of water resources, and potentially hinder successful implementation. Another factor that could introduce uncertainty is the competing demand for reclaimed water from multiple sectors. This study reveals that in areas where the highest level of reuse (scenario RW) is implemented, such as certain counties or states like Arizona and Nevada, there may be limited reclaimed water available for new users from other sectors (Figure 4). Moreover, in regions facing drought and reduced stream flow and reservoir levels, like CA, other sectors are likely to increase their use of reclaimed water, further constraining the availability of reclaimed water for algae production. These southern regions, renowned for their favorable conditions for algae pond facilities and high algae productivity, play a crucial role. Future work will focus on these factors that are essential to the feasibility of production on a larger scale.

5. Conclusions

This study explores the viability of using municipal reclaimed water for algae biofuel production by co-locating algae pond facilities with WWTPs. The analysis examines three scenarios at the state and county levels, revealing substantial water resources (584 BL–2694 BL) in identified algae production counties across U.S. southern states. These resources can potentially support the production of 14–42 MMT of algal biomass per year, resulting in 10–29 BL of biofuels. Implementing reclaimed water use for algae production would significantly expand water reuse practices throughout the U.S. and quadruple current biodiesel production in the U.S. However, up to 455 counties would experience heavy traffic from reclaimed water delivery trucks within their boundaries. To minimize the water transport burdens, one scenario (RW100) restricts reclaimed water supply from 455 down to 264 counties that can fully meet the water demand, allowing 612 BL of reclaimed water to be available to produce 12 BL of biofuels, and doubling current biodiesel production.

These results provide quantitative insights into the potential scale of reclaimed water-based algal biomass production and highlight the logistical and operational challenges associated with infrastructure constraints. The datasets compiled and the methodology developed in this study can be applied to similar investigations in other countries and regions to support data-driven decision making. The findings emphasize the importance of improving existing wastewater treatment infrastructure for reclaimed water use, particularly in southern states, to facilitate the deployment of algae biodiesel production.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w15173123/s1: Supporting Materials SI, Supporting Materials SII.

Author Contributions: M.W. designed the study and developed the concept, methodology, and scenarios, while M.H. conducted the data acquisition, and S.M. and M.W. completed the data analysis. M.H. and S.M. developed the geospatial map illustrations. M.W. interpreted the results and drafted the manuscript. M.H. and S.M. reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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