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High-rate algal ponds in wastewater treatment: a critical look at recent developments

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Conventional wastewater treatment systems carry a significant environmental footprint, underscoring the urgent need for more sustainable alternatives. Microalgae-based wastewater treatment systems represent a promising and eco-friendly alternative, by enabling simultaneous wastewater treatment and biomass production. Various system configurations including waste stabilization ponds, photobioreactors, sequential batch reactors, biofilm reactors, column bubble systems, hybrid systems, and high-rate algal ponds, leverage photosynthesis and microalgae–bacteria symbiosis to effectively remove nutrients and organic matter. Photobioreactors provide enhanced control of environmental conditions and optimize biomass production, while sequential batch and biofilm reactors prioritize biomass growth. Column bubble systems utilize granular biomass for efficient treatment and high-rate algal ponds rely on the symbiosis of algae and bacteria to improve treatment efficiency. Raceway pond design is customized to meet specific operational requirements, with nutrient loading and microalgae species selections playing crucial role in determining biomass yield and nutrient uptake. High-rate algal ponds (HRAPs) are engineered systems to optimize and intensify the algal–bacterial symbiotic processes, providing a high-efficiency framework for nutrient removal and biomass production. Environmental conditions such as temperature, light intensity, and pH affect the growth and dominance of different microalgae species in open pond systems. This review critically synthesizes recent findings to identify operational gaps and facilitate scale-up and implementation of nature based solutions in current practices. It focuses on raceway pond systems, examining key parameters governing algal–bacteria symbiosis, biomass production, nutrient removal, and harvesting efficiency. Finally, it provides a comparative assessment with alternative microalgae cultivation technologies in terms of performance and sustainability.

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Water impact

This review evaluates microalgae-based systems as eco-friendly alternatives to conventional wastewater treatment, focusing on enhancing nutrient removal and water reclamation efficiency. By comparing reactor configurations like raceway ponds and photobioreactors, it identifies key operational parameters to optimize treatment performance. This work provides a framework for toward low-cost water infrastructure that prioritizes resource recovery and reduces the environmental footprint of water utilities.

Introduction

Biological processes have long been recognized as effective technologies for wastewater treatment,[1] widely used in wastewater treatment plants (WWTPs) to efficiently remove organic carbon and nutrients.[2] Among these, microalgae-based biological treatment has emerged as a promising alternative of reducing nutrient loads discharged to aquatic ecosystems.[3,4] During photosynthesis, microalgae cultures, can also absorb CO_2 from the surrounding environment and convert it into organic compounds, such as sugars and lipids, using sunlight as an energy source.[5] This process not only captures CO_2 but also produces oxygen as a byproduct, positioning microalgae a valuable tool in mitigating greenhouse gas emissions.[6,7]

In recent years, microalgae have gained significant attention as an alternative biological treatment system with several applications in wastewater treatment.[8,9] Microalgae are photosynthetic, aquatic, single-celled organisms that can reduce the harmful effects of sewage effluent[10] and mitigate eutrophication in aquatic environments.[11] Algal biomass has potential for renewable hydrocarbon-based biofuel production, offering higher yields than traditional oil-producing plants.[12,13] In addition to their low operational cost and simplicity, algae-based wastewater treatment systems offer the advantage of nutrient and energy recovery.[14–19]

Microalgae-based systems include waste stabilization ponds (WSPs), photobioreactors (PBRs), sequential batch reactors

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(SBR), biofilm reactors, column bubble systems, hybrid systems and high-rate algal ponds (HRAPs).[19] Photosynthesis in WSPs generates oxygen, while symbiotic interactions with bacteria facilitates the removal of organic matter and nutrients.[20] Optimal hydraulic retention time (HRT) ranges from 4 to 7 days, in order to achieve phosphorus removal efficiencies between 63 to 93%.[21] During low-temperature periods with temperatures below 10 °C, HRT may need to be increased to up to 9 days.[21,22] PBRs enhance microalgae photosynthesis and biomass concentration,[23] offering superior control over environmental parameters compared to open pond systems.[24] SBR operate in a fill-and-draw basis, treating wastewater in batch reactors containing microalgae or microalgae–bacteria consortia.[6,25] Biofilm reactors are designed to promote algal biomass growth.[16,26–28]

Column bubble systems feature a high height-to-diameter ratio, and air supplied from the bottom of the reactor, and typically are used with granular biomass.[29–32] Hybrid systems integrate microalgae with other systems such as activated sludge, constructed wetlands, and immobilization processes.[24,33,34] Hybrid systems require less energy and have lower operational cost.[35] Recent studies have shown that incorporating activated sludge into algal cultures enhanced nutrient removal 10, and facilitated biomass settling.[36,37] The combination of constructed wetlands (CWs) and microalgae may further increase removal efficiencies of organic matter and total nitrogen by 27 and 10%, respectively.[38] HRAPs, or raceway ponds, represent a combination of WSP and PBR systems.[39] They offer a cost-effective solution for treating various types of wastewater, including municipal, agricultural and industrial.[40–42] Typically, HRAPs are paddlewheel-mixed open raceway ponds that mimic conventional oxidation ditches while evaluating the efficiency of algal cultures.[43,44] HRAPs face several limitations, including high evaporative water loss, CO_2 escape, large land requirement, microbial competition (*i.e.* bacteria and microalgae), and energy demand for mixing.[45,46] Raceway ponds are complex systems and for that reason various models have been developed to simulate their performance in a long-term procedure, considering the environmental conditions.[47–49] Several pilot and full-scale HRAP systems have already been implemented worldwide, particularly in regions with favorable climatic conditions such as Spain, Australia and the United States.[45,46] These systems demonstrate the feasibility of algae-based wastewater treatment at commercial scale, particularly for nutrient removal and biomass recovery. However, large land requirements and biomass harvesting costs remain significant barriers to widespread industrial adoption.[47–49]

This work critically examines the microalgae–bacteria consortium in outdoor raceway systems for wastewater treatment. Design parameters play a crucial role in HRAP efficiency.[50] In addition to geometric design, environmental factors such as temperature, solar radiation, and daylight duration significantly affect biomass growth and nutrient removal.[51] This works aims to present the recent progress in raceway ponds technology by evaluating performance parameters, comparing their efficiency with other algal cultivation systems, and assessing optimal design and environmental conditions for effective nutrient removal and biomass growth. It also explores harvesting methods, potential biomass applications, and provides a critical synthesis of advancements, challenges, and future industrial prospects. The paper aims to highlight the benefits of microalgae–bacteria consortia, targeting environmental scientists and processes engineers toward implementing energy-efficient and effective nature-based treatment solutions in wastewater treatment practice.

Raceway configuration and design parameters

Pond geometry

Raceway systems are typically long, narrow ellipse-shaped open ponds, equipped with baffles.[50,52] The length-to-width (L/W) ratio is a critical parameter for optimizing geometry and minimizing the formation of "dead zones",[52] areas where biomass is not thoroughly mixed, leading to biomass sedimentation[52] while the area ranges from lab-scale (0.06

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m^2) to full scale (12 500 m^2). The L/W ratios reported in the literature range from 2 to 10.[52] When the L/W ratio is below eight, the pond functions as a well-mixed reactor, while at L/W ratio above eight, it behaves like a plug-flow reactor.[52] Other researchers examined L/W ratios from 4 to 25, reporting that better mixing was achieved at ratios below 10. Increasing pond depth (*i.e.* 0.8 m) can improve mixing and reduce dead zones, however, deeper ponds do not favor biomass production.[50]

Several materials are used for the construction of the raceway ponds, such as concrete, cement, fiberglass, geomembrane liner and even epoxy-coated concrete, depending on scale.[52] Laboratory-scale ponds are usually made of fiberglass or PVC, while pilot-scale systems often utilize concrete.[53,54]

Scale

The required area for raceway ponds depends on the level of wastewater pre-treatment as well as environmental conditions. The scale-up of ponds has been studied to evaluate algal efficiency in nutrient removal biomass productivity. Other examined *Nannochloropsis salina* in outdoor ponds, of 3, 10 and 120 m^2, fed with synthetic wastewater.[5] Higher biomass productivity was observed in larger ponds using paddle wheels and CO_2 supplementation. Conversely, smaller ponds (area of 5 and 30 m^2) achieved 33 and 22% higher biomass production and nutrient removal, respectively, compared to a 1000 m^2 pilot-scale pond.[53] Although, increased land requirements can be a drawback for HRAP, appropriate design, such as constructing ponds in series, can mitigate space requirements.[55] The remediation of heavy metals in HRAPs faces significant practical challenges in high-volume industrial settings. While microalgae act as effective green adsorbents for metals like chromium and lead,[56] the complexity of industrial effluents can inhibit algal growth. Scaling up these processes requires a robust techno-economic analysis to balance treatment efficiency with the costs of biomass management and commercial-scale implementation.

Depth

HRAPs are generally shallow basins with depths less than 50 cm, mixed by paddle wheels to circulate flow[74,88] (Fig. 1a, Table 1). Higher concentrations of chl-a, even by six times, can be achieved in ponds with a depth of 20 cm compared to 40 cm.[63] Although, shallower depths enhance biomass production they do not significantly affect nutrient removal.[63] CO_2 addition enhances the chl-a concentration in deeper ponds but has minimal impact in shallow ones.[63] However, in a raceway system with depths of 20 and 40 cm treating primary settled wastewater, nutrient removal was increased with depth, whereas chl-a concentration was lower in the deeper pond.[83]

A raceway system usually has a depth of 0.2 to 0.3 m (Fig. 1a) however, fewer studies examined ponds with higher

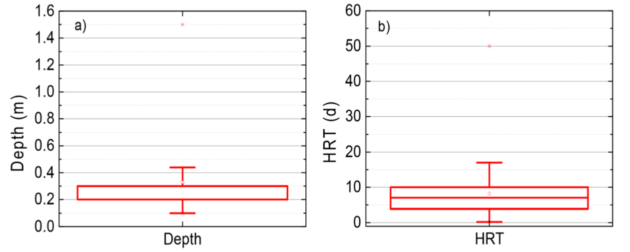

Fig. 1 Range of a) depth and b) HRT in raceway ponds. Data are based on studies for depth[5,17,43,44,46,55,58,59,61,63–66,69,70,72–76,79–81,91] and for HRT.[5,17,43,44,46,55,58,61,63–66,69,70,72–76,79–81,91]

depths even over that 1 m but mentioned the importance of additional lightning. In higher depth HRAPs, up to 1.2 m bottom-mounted LED-lights were installed and achieved similar organic matter and nitrogen removal as in the 30 cm depth pond.[85] Chlorophyll concentration varied within the water column depending on depth.[85]

Generally, the increase of pond depth reduce dead zones,[50] however, it results in lower algal productivity[89] due to light attenuation. Despite the algal productivity, effective nutrient removal may still occur independently. This suggests that nutrient uptake in HRAPs is not solely driven by high growth rates but is also supported by cellular storage mechanisms and bacterial interactions, even under suboptimal light conditions.[90]

Mixing and air supply

Efficient mixing is important to prevent cell deposition, concentration gradients, and thermal stratification, while ensuring optimal nutrient and light availability.[45] Common mixing systems include: a) paddle wheels,[92] b) screw pumps[54] and c) airlift systems.[93] In a typical raceway system, a paddle wheel is often used for the mixing of the system either by the flow or by a motor with velocity over 0.1 m s^{-1} in order to avoid microalgae sedimentation.[52] The paddle-wheel system can enhance biomass contact with wastewater and facilitates CO_2 transfer, promoting microalgae growth.[43,94] Air pumps are often used to increase CO_2 concentration.[68,80,86] CO_2 addition at ponds with depths of 0.35 and 4 m resulted in enhanced biomass productivity even by two times, leading to biomass production of 12 and 20 g m^{-2} d^{-1} respectively.[64] The addition of CO_2 resulted an increase of algal biomass productivity by three times, from 13 to 38 g m^{-2} d^{-1} at a water depth of 0.15 m.[86] Using CO_2 from flue gas, instead of pure CO_2, enhances phosphorus and COD removal.[79] Due to intense CO_2 stripping in the mixed liquor of a raceway pond, CO_2 addition from flue gas, compared to operation without it, improved pH control but did not enhance wastewater treatment performance or biomass production in a 0.1 m depth raceway system.[79] Although, biomass content in nitrogen and phosphorus decreased in the case without CO_2 supply, the content of biomass in lipids, proteins, and carbohydrates was almost the same.[79] The addition of CO_2 to

Table 1 Compilation of pilot-scale HRAPs with main operational characteristics

Ref.	Volume	Depth	HRT	Operation mode	Place	Duration	Wastewater type	Algal species	Biomass concentration		Biomass production	Removal			
									Initial	Final		COD	NH_4^+	NO_3^-	PO_4^{3-}–P
	m^3	m	d			d			g L^{-1}	g L^{-1}	g m^{-2} d^{-1}	%	%	%	%
10	0.7		1.75	Batch	Outdoor covered	52	PE	Mixed culture	0.7[a]		1.25[a]		94		93
43	300	0.3	30	Batch	Outdoor	32	SE N : P 10 : 1	*Scenedesmus obliquus*	0.88 DCW	0.98 DCW			100	89.40	79.01
57				Batch	Indoor	12	PE	*Scenedesmus obliquus*	0.1 TSS	1.6–2.6 TSS			42–95		16–100
58	0.533	0.3	4.6	Batch	Outdoor	10			0.12 TSS	0.5 TSS					100
58	0.266	0.15	3.1	Batch	Outdoor	10			0.12 TSS	0.61 TSS					100
58	0.533	0.3	5.4	Continuous	Outdoor	10			0.12 TSS	0.4 TSS					100
59	0.266	0.15	3.9			10			0.12 VSS	0.485 VSS					100
59	0.47	0.3	4.5	Batch	Outdoor	260	PE		0.2 VSS			39	39		37
60			2.2	Batch	Outdoor	22	AE	Mixed culture					87		57
60			3.3	Batch	Outdoor	33	AE						83		39.70
60			4.1	Batch	Outdoor	41	AE						90		40
49	0.88			Batch		189	AG	Algae–bacteria	0.003 TSS	0.004 TSS					
47	17	0.3	5	Batch	Simulated outdoor	412	PE	Algae–bacteria	0.013 TSS		15.5 TSS				
48	12	0.46	10	Batch	Simulated outdoor	50	AG	Algae–bacteria			17 TSS				
61	0.18	0.15	50	Batch	Simulated outdoor	303	PE	Mixed culture		0.38 TSS					
62	0.95			Batch	Outdoor		BG-11	Mixed culture							
62	0.95			Batch	Outdoor		PE	Mixed culture							
62	0.95			Batch	Outdoor		PE	Mixed culture							
63	0.66	0.2	8	Batch	Outdoor	8	DW	Algae–bacteria	0.05 VSS	0.1 VSS		43.1	76.8		58.2
63	0.99	0.3	8	Batch	Outdoor	8	DW	Algae–bacteria	0.05 VSS	0.07 VSS		40.6	40.9		22
63	1.32	0.4	8	Batch	Outdoor	8	DW	Algae–bacteria	0.05 VSS	0.06 VSS		42.2	39.4		22
63	0.66	0.2	8	Batch	Outdoor	8	DW	Algae–bacteria	0.05 VSS	0.07 VSS		42.2	84.4		48.3
63	0.99	0.3	8	Batch	Outdoor	8	DW	Algae–bacteria	0.07 VSS	0.065 VSS		42.1	47.7		15.4
63	1.32	0.4	8	Batch	Outdoor	8	DW	Algae–bacteria	0.065 VSS	0.065 VSS		40.4	62.5		7.7

Table 1 *(continued)*

Ref.	Volume	Depth	HRT	Operation mode	Place	Duration	Wastewater type	Algal species	Biomass concentration Initial	Biomass concentration Final	Biomass production	Removal COD	Removal NH_4^+	Removal NO_3^-	Removal PO_4^{3-}–P
	m^3	m	d			d			$g\ L^{-1}$	$g\ L^{-1}$	$g\ m^{-2}\ d^{-1}$	%	%	%	%
63	1.32	0.4	8	Batch	Outdoor	8	DW	Algae–bacteria	0.065 VSS	0.08 VSS		47.5	56.6		22.8
64	4375	0.35			Outdoor		PE	Algae–bacteria							
64	2850	0.3	4–8	Continuous	Outdoor		PE	Algae–bacteria			12–20 TS				
65	2	0.4	65	Batch			UASB-E	Algae–bacteria				90			99
66	0.464	0.3	10	Batch	Outdoor	245	Piggery wastewayer	Mixed culture				76			
67	0.464	0.3	10	Batch	Outdoor	44	UASB-E	Mixed culture							
68	9.6	0.3	3–7	Continuous	Outdoor	426	UASB-E	Mixed culture			13.2 TSS		53		
68	9.6	0.3	5–10	Continuous	Outdoor	426	UASB-E	Mixed culture			8.3 TSS		62		
68	9.6	0.3	3–7	Continuous	Outdoor	426	UASB-E	Mixed culture			17.2TSS		51		
68	9.6	0.3	5–10	Continuous	Outdoor	426	UASB-E	Mixed culture			12.9 TSS		53		
8			8	Batch		8	PE		0.05 TSS	0.65 TSS			72–83		100
69	0.6	0.15		Batch	Laboratory	140	DW	*Chlorella variabilis* TH03–bacteria consortia			11.1–15.3 TSS	80–88	94–99.8	94–99.6	100
70	1.9	0.4	6	Continuous	Outdoor	270	DW	Algae–bacteria				80	90		45
70	1.9	0.4	6	Continuous	Outdoor	2710	DW	Algae–bacteria				60	90		50
71	0.47	0.3	7–10	Batch	Outdoor	406	DW	Algae–bacteria			12.7 TSS	35			43
71			4–8	Batch	Outdoor	406	DW	Algae–bacteria			14.8 TSS	38			32
72	0.47	0.3	0.4–0.8	Continuous	Outdoor	365	PE	Mixed culture			3.3–25.8 TSS	80	97		
73	18	1.5	63		Outdoor	63	AG	Mixed culture		0.186			1200[b]		132[b]
17	0.47	0.3	4	Continuous	Outdoor	8	DW	Mixed culture				53	93		67
17	0.47	0.3	8	Continuous	Outdoor	8	DW	Mixed culture				48	92		65
74	1.2	0.2	10	Continuous		120	SE	Algae–bacteria			5.5 TSS		96		71
75	0.5	1.5	3		Outdoor	4	PE	Algae–bacteria							
75	0.5	1.5	3		Outdoor	8	PE	Algae–bacteria							
76	8	0.44	4	Batch	Outdoor	65	SE	*Hydrodictyon reticulatum*		1700 TSS					80
76	8	0.44	4	Batch	Greenhouse	65	SE	*Hydrodictyon reticulatum*							
5	0.6	0.2		Batch	Outdoor	21	NMR	*Nannochloropsis salina*			0.2 TSS				
5	1.5	0.25		Batch	Outdoor	30	NMR	*Nannochloropsis salina*			19.5 TSS				
5	20	0.17		Batch	Outdoor	80	NMR	*Nannochloropsis salina*			15 TSS				
77	11.8	0.135	0.2	Semi-continuous	Greenhouse	365	PE					85–95		50–80	365
78	0.3	0.3	20	Batch	Outdoor	40	F/2-Si + seawater	*Dunaliella salina*		0.549 TS					
79	0.7	0.1	3.3	Semi-continuous	Outdoor	97	DW	Algae–bacteria		0.425 TSS		83	95		55
79	0.8	0.1	3.3	Semi-continuous	Outdoor	97	DW	Algae–bacteria		0.441 TSS		85	93		59
79	0.85	0.1	3.3	Semi-continuous	Outdoor	97	DW	Algae–bacteria		0.429 TSS		81	94		58
80	0.88	0.3		Batch	Outdoor	6	AG	*Chlorella* sp. and *Scenedesmus* sp.	0.47		8.5 TSS	29	80		
80	0.88	0.3	11	Batch	Outdoor	5	AG	*Chlorella* sp. and			8.1 TSS				

Table 1 *(continued)*

Ref.	Volume	Depth	HRT	Operation mode	Place	Duration	Wastewater type	Algal species	Biomass concentration Initial	Biomass concentration Final	Biomass production	Removal COD	Removal NH_4^+	Removal NO_3^-	Removal PO_4^{3-}–P
	m^3	m	d			d			g L^{-1}	g L^{-1}	g m^{-2} d^{-1}	%	%	%	%
								Scenedesmus sp.							
80	0.88	0.3	8	Batch	Outdoor	12	AG	*Chlorella* sp. and *Scenedesmus* sp.			7.4 TSS				
80	0.88	0.3	10	Batch	Outdoor	11	AG	*Chlorella* sp. and *Scenedesmus* sp.			7.2 TSS				
80	0.88	0.3	10	Batch	Outdoor	25	AG	*Chlorella* sp. and *Scenedesmus* sp.			7.1 TSS				
80	0.88	0.3	10	Batch	Outdoor	45	AG	*Chlorella* sp. and *Scenedesmus* sp.			6.9 TSS				
80	0.88	0.3	10	Batch	Outdoor	25	AG	*Chlorella* sp. and *Scenedesmus* sp.			7.1 TSS				
81	0.42	0.15			Greenhouse			Mixotrophic							
39	22	0.3	6	Batch	Outdoor	36	PE	Algae–bacteria		200 VSS			41	100	57
55	1.44	0.4		Batch	Outdoor	8	DW	Algae–bacteria		0.25 SS					
82	0.012	0.2		Batch	Outdoor covered	24	DW	Algae–bacteria	0.096 TS	0.214 TS		100	93.2	17.1	24.2
82	0.024	0.4		Batch			DW	Algae–bacteria							
82	0.036	0.6		Batch			DW	Algae–bacteria							
83	0.45	0.2			Outdoor		PE					63–78			
83	0.67	0.3			Outdoor		PE					64–77			
83	0.89	0.4			Outdoor		PE					58–76			
53	1.5		8				PE								
53	90		8				PE								
40	2900	0.3	8	Batch	Outdoor	180	AE	Algae–bacteria							
84	3.7	0.25	3	Batch	Outdoor	180	Brewery AE			0.35 TS					
84	1.7	0.115	3	Batch	Outdoor		SE								
85	1.25	0.3	10	Batch	Outdoor	720		Mix culture				50–67			
85	1.25	1.2	10	Batch	Outdoor							48–87			
86	0.5	0.15	17	Batch	Outdoor	18	DW	*C. variabilis* TH03			13.1	83.1	97.7		99.9
86	0.5	0.15	17	Batch	Outdoor		DW	*C. variabilis* TH03			38.5	89.8			
41			35	Batch											31
87	64	0.32	5	Batch	Outdoor		PE			0.115 TSS					91

[a] OD 750 nm. [b] mg d^{-1}. Note PE: primary effluent; SE: secondary effluent; DW: domestic wastewater; AE: anaerobic effluent; AG: agriculture wastewater; UASB-E: UASB effluent; DCW: dry cell weight; TS: total solids; TSS: total suspended solids; VSS: volatile suspended solids.

raceway ponds with a surface area of 1.93 m^2 and a depth of 0.15 and 0.3 m resulted in similar biomass concentration under both batch and continuous operation mode. However, biomass lipid content was higher in the continuous mode.[57]

Simulation of raceway pond configurations demonstrated that pond geometry affects flow velocity, which varied from 0.20 to 0.40 m s^{-1}.[50] A flow velocity of approximately 0.30 m s^{-1} is often adopted in the literature as a target velocity for microalgae cultivation,[50] in order to enhance the flocculation of microalgae.

Hydraulic retention time

The HRT varies depending on the scale of the raceway system, the type of wastewater treated, environmental conditions, and the microalgae species employed. HRT may also affect the bacterial population within algal–bacteria consortia, as longer HRTs during summer have been shown to result in higher bacterial biomass than those operated with shorter HRTs.[40,95] According to the literature, typical HRT values range from 4 to 10 days (Fig. 1b).

The cultivation of *Hydrodictyon reticulatum* in a 8 m^3 raceway system in a greenhouse over a 40-day period at a constant HRT of 4 d achieved 80% phosphates removal.[76] In contrast, other researchers[10] investigated nutrient removal in a 0.7 m^3 raceway pond using a mixotrophic culture of *Galdieria sulphuraria*, treating varying ratios of activated sludge and primary effluent (ranging from 10:90 to 25:75) over 30 days. At an HRT of 7 d, they observed over 93% removal of ammonia and phosphorus. The impact of different HRTs in two open HRAPs with algal–bacteria cultures, operating at 10 and 8 d, and 7 and 5 d, in the first and second period, respectively, have been examined.[96]

The HRAP with a 10 d HRT exhibited 57% higher average nitrogen removal compared to the operating at 7 d. Complete nutrient removal (100%) was also observed in a laboratory-scale open raceway system containing microalgae and bacteria operating at an HRT of 1.0 d, treating primary and secondary treated wastewater.[97] The optimal HRT for a *Chlorella vulgaris* culture in a 3.8 m^2 raceway pond was 1.2 d, ensuring both high growth rates and sustained treatment capacity over long-term operation.[69]

Generally, the HRT of an HRAP system is mainly affected by the environmental conditions and the desired efficiency in nutrient removal. Usually, higher biomass concentration may reduce nutrient centration faster due to higher biomass needs.[33]

Pond performance and removal mechanism

Wastewater and nutrient characteristics

Various types of wastewaters have been treated using HRAPs including primary[40,64,75,97–99] and secondary treated wastewater,[76] synthetic wastewater, industrial,[66,100,101] or even agricultural wastewater.[73,84] Wastewater augmented with fertilizers showed a significantly lower presence of pathogens than wastewater, which however showed greater pathogens reduction from inlet to outlet due to treatment.[101]

Nutrient removal efficiency varied from 35 to 100% across the studies reviewed (Fig. 2a). Higher removal rates were observed for nitrates and ammonia, with average efficiencies of 95 and 85%, respectively. The average removal efficiencies for COD and phosphorus were almost 56% for both parameters. Wastewater characteristics, including carbon impact and N:P ratio, is a critical factor in algal wastewater treatment.[19] In open pond systems, the C:N ratio of influent wastewater varies based on atmospheric conditions, CO_2 availability, and wastewater type.[19] Typically, primary effluent has a C:N ratio of about 8:1,[102] while, secondary effluent averages around 3:1.[45] For optimal microalgae growth and nutrient removal in raceway pond systems, the C:N ratio should ideally be between 10:1 and 15:1. This range provides sufficient carbon to support photosynthesis and nitrogen assimilation, both essential for biomass production and effective nutrient uptake from domestic wastewater.[103] However, effective nutrient removal may be achieved without an extremely high growth rate, as far as an optimum nutrient ratio is attained.[45]

The optimal N:P ratio for microalgae growth in wastewater treatment varies depending on the algal strain.[43] For instance, the optimum N:P ratio range for *Scenedesmus*

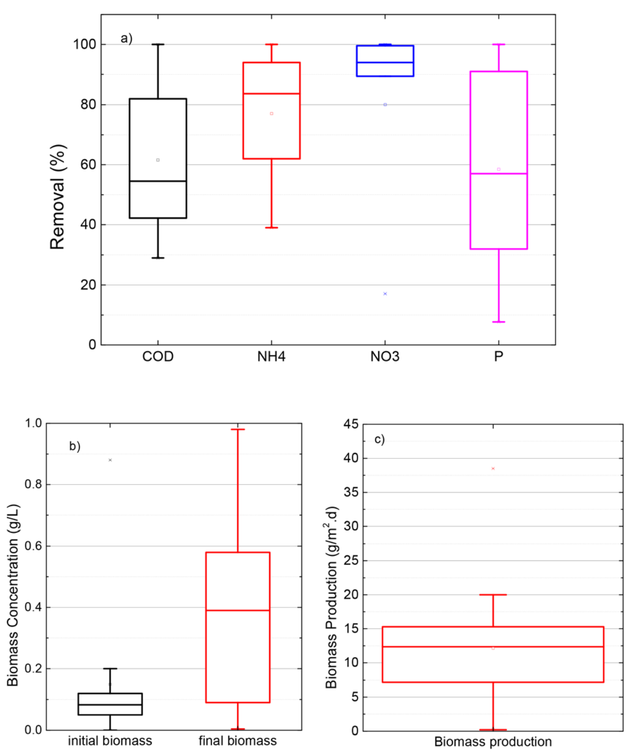

Fig. 2 Range of a) nutrient removal, b) initial and final biomass and c) biomass production in raceway ponds. Data are based on studies for COD,[17,59,63,69,72,79,105] for ammonia,[8,10,17,45,59,66,69,71,74,76,80,96,100,101] for nitrates,[39,43,69,77] for phosphorus,[8,10,17,39,43,57,58,63,65–67,69–71,73–77,79] for initial and final biomass concentration,[10,43,48,57,58,63,79] and for biomass production.[5,10,47,48,76,79,80]

sp. is from 9 : 1 to 13 : 1,[58] while other studies identified an optimal N : P ratio of 10 : 1 when testing ratios of 4 : 1, 10 : 1, and 68 : 1.[43] In algal–bacterial open ponds treating municipal wastewater, an N : P ratio of 5 : 1 to 30 : 1 promotes faster nitrogen uptake.[18,104]

Wastewaters with an excessively low N : P ratio, such as 3 : 1 (*e.g.* secondary effluent) or an overly high ratio, such as 16 : 1, may hinder algal growth, underscoring the importance of strain selection for wastewater cultivation.[18] So, the optimal N : P ratio for primary treated wastewater is 9 to 13 : 1,[43,58] with an optimum C : N : P ratio of 33.3 : 6.3 : 1.[106] In contrast, secondary treated wastewater has an average C : N : P ratio of 14.28 : 4.85 : 1 (C : N = 2.94 : 1 and N : P = 4.85 : 1).[106] Variations in optimal C : N and N : P ratios across studies highlight that algal species selection is a critical factor in algae-based wastewater treatment for nutrient removal. Consequently, the reliability of the system depends more on operational conditions and the specific regime for mixing secondary treated effluent with the algae than on the bioreactor design.[19]

Microalgae species

Microalgae growth and nutrient removal vary depending on the species employed.[62,107,108] In open systems, the species dominate influenced by the operational and environmental conditions rather than the starting species.[72,109] Pure microalgae cultures have been studied in raceway systems fed with freshwater,[43] wastewater[76] and saline water.[5] However, in open pond system, microorganisms from the surrounding environment can enter the tank and significantly alter the microbial consortia. For that reason, the efficiency of mixotrophic and microalgae–bacteria cultures has been investigated.[10,110] Mixotrophic cultivation offers metabolic flexibility, helps overcome light limitations and shading effects, enhance growth rates, and protects cells from light-induced damage.[111,112] Other researchers initiated outdoor raceway system without seeding bacteria or microalgae; nevertheless, a bacteria–microalgae consortium naturally developed after 19 days while treating synthetic wastewater.[39] After nearly a month, with an HRT of 6 d, the culture successfully removed nutrients from synthetic wastewater and produced algae-bacteria biomass.[39] The combination of microalgae with macrophytes in a raceway system enhanced phosphorus removal to levels below 1 mg P/L and practically eliminated. This system was fed with effluent from an anaerobic reactor treating municipal wastewater at an HRT of 4.1 d.[60] However, other studies mentioned that genetic modification of algal may increase nutrient removal[113] and help biomass harvesting.[114]

Environmental conditions

Environmental conditions affect algal growth; however microalgae exhibit greater adaptability to environmental fluctuations compared to bacteria.[9,66] Casagli and coworkers[47,48] reported that hydraulic loads are significantly affected by weather conditions (*i.e.* rainfall and evaporation rates), leading to dilution or concentration of soluble and particulate compounds within the reactor. These changes impact bioprocess rates and light availability. In addition, water loss in HRAPs can alter the ionic composition of the medium.[107]

In order to evaluate the effect of temperature, hydrodynamics, and environmental conditions on pond design, numerical models have examined temperature ranges from 0 to 30 °C and pond depths from 0.1 to 0.3 m.[115] Elevated temperatures enhance biomass growth, although temperatures above 28 °C also increase evaporation. Light intensity further promotes biomass growth; for this reason, Min *et al.* (2021)[76] used a device to direct sunlight into a 0.44 m deep and supplemented it with an underwater light source (50 μmol m^{-2} s^{-1}) to improve underwater illumination.

Seasonal and environmental variations have shown to affect algal growth.[61,66,77] The average final biomass concentration increased by 80%, compared to initial levels (Fig. 2b). In outdoor systems, environmental temperature affects both wastewater treatment efficiency and biomass productivity.[51,70] The average biomass productivity was approximately 12.5 g m^{-2} d^{-1} (Fig. 2c), although, higher values up to 38 g m^{-2} d^{-1}, were observed in a raceway system treating domestic wastewater with a *Chlorella vulgaris*–bacteria consortium.[86]

Generally, the optimal temperature range for microalgae ranges is between 16 and 27 °C.[100] However, different microalgae strains and species have distinct temperature preferences.[43] For example, the favorable temperature for *Parachlorella kessleri* growth was from 21.6 to 31.8 °C.[99] Temperatures lower than 16 °C slow the growth of green microalgal species such as *Chorella* and *Chlamydomonas*, while temperature above 35 °C is detrimental.[100] During winter, lower temperatures necessitate longer HRT, up to 9 d.[84] Long-term studies have reported seasonal variations in biomass production and nutrient removal, with higher concentrations in summer and lower in winter.[72,80]

Biomass productivity and nutrient removal in HRAP are affected by temperature increases from 5 to 25 °C and changes in photoperiod from 6 : 18 h (light : dark) to 12 : 12 h, with illumination at 250 μmol s^{-1} during the light phase.[8] In summer, ammonia stripping and nitrification are the main nutrient removal mechanisms, while phosphate removal occurs mainly through assimilation and precipitation due to elevated pH levels.[66,116] At temperatures above 25 °C, nitrification was the main mechanism for TKN removal, and ammonia volatilization becomes negligible in algal–bacterial consortium treating piggery wastewater.[66] Under high organic loading rates, nitrification and denitrification processes occur simultaneous.[66]

Chl-a concentration is affected by environmental conditions and the surface area of an HRAP.[66] During summer, raceway area plays a crucial role in increasing chl-a concentration; however, in winter, chl-a concentrations remain similar in ponds of 5 m^2 and 1 ha.[53]

Light spectrum also affects the growth of *Dunaliella salina* MUR 08.[78] Blue light increases chl-a concentration, while red light enhances biomass productivity, lipid, and carotenoid content.[78] Red light has been used in microalgae-based wastewater treatment due to its efficient energy utilization and emission spectrum, which aligns with the absorption peaks of chlorophylls a and b, (430 and 664 nm).[85] However, higher-intensity radiation may cause overheating.[100]

Nutrient removal mechanism

In open pond reactors, microalgae coexist with bacteria, protozoa, and other microorganisms.[91] Microalgae–bacteria consortia have shown promise for advanced nutrient removal from wastewater. The bacteria associated with microalgae can perform processes like nitrification and denitrification at low oxygen concentrations, contributing to nitrogen removal.[33,74] These mechanisms vary depending on factors such as the species involved, environmental conditions, and wastewater composition.[116,117]

Autotrophic bacteria oxidize ammonia through nitrification to nitrite and nitrate. Ammonia-oxidizing bacteria (AOB) convert ammonia to nitrite, and nitrite-oxidizing bacteria (NOB) convert nitrite to nitrate.[118] Nitrifying bacteria convert ammonia into less toxic forms, making it more readily available for uptake or reuse by microalgae or other organisms.[21]

Under mixotrophic conditions, algae–bacteria metabolic interactions could promote the synergistic rather than competitive growth. The metabolism of organic carbon provides an internal source of carbon dioxide for photosynthesis, which in turn enriches the water with oxygen supporting bacterial growth.[119] Microalgae photosynthesis increases dissolved oxygen (DO) in the water column enhancing nitrification. The increased DO in water further enhances the action of nitrifying bacteria. However, oxygen rich conditions inhibit bacteria denitrification,[120] which typically occurs under anoxic conditions.[33] Nutrient availability, such as nitrogen and phosphorus, affects the growth and activity of both microalgae and bacteria. A balanced nutrient profile is crucial for optimal COD removal in HRAPs. Organic matter and nitrogen removal efficiency varies with nutrient concentrations and the organic matter to nitrogen ration, depending on environmental conditions.[19] In mixotrophic cultures, organic carbon sources enhance nutrient uptake and organic matter removal due to the presence of heterotrophic bacteria and microalgae, providing additional energy and supporting metabolic activities.[121,122] These synergistic interactions are key to effective COD removal.[123] Ammonia-nitrogen is a vital nitrogen source for microalgae growth,[124] supporting the synthesis of lipids, proteins and carbohydrates.[125] Nitrogen in wastewater can be removed by microalgae through direct assimilation or indirectly by physicochemical processes.[126] Nitrogen assimilation by microalgae depends on the substrate used (Fig. 3).

Microalgae prefer ammonium over nitrate or nitrite due to the lower energy required for its conversion into amino acids and proteins.[127,128] Inside the algal cell, ammonium is converted to glutamine (Gln) from glutamic acid (Glu) *via* the enzyme glutamine synthetase (GS), while Glu also contributes to amino acid synthesis.[127] Ammonium enters mitochondria and synthesize glutamic acid in the presence of 2-oxoglutarate (2-OG).[129] In the chloroplast, ammonium supports a cycle of Glu and Gln synthesis.[129] (Fig. 3). Nitrate enter the vacuole for amino acid storage,[130] and in the chloroplast, it is reduced to nitrite by nitrate reductase (NR), then to ammonium by nitrite reductase (NiR).[127] Organic nitrogen (Org-N) requires more energy to be oxidized to nitrate and nitrite.[131]

Photosynthesis increases the pH of the culture, promoting indirect nitrogen removal. Elevated pH leads to the formation and volatilization of free ammonia.[132] The pK_a of the ammonium ion is 9.25 at 25 °C,[133] and above this pH, ammonia prevails. Reported ammonia-nitrogen removal due to elevated pH ranges from 38 to 100% for cyanobacteria *P. bohneri* at pH from 7.9 to 9.2 (ref. 134) and 53 to 82% for *S. obliquus* under varying temperatures and mixing regimes at pH from 9 to 11.[135]

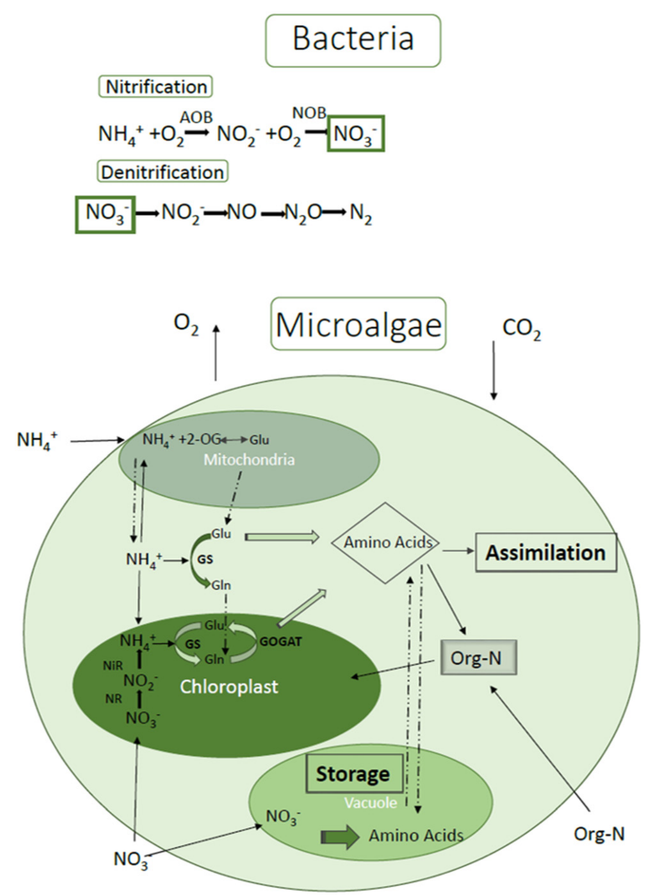

Fig. 3 Nutrient removal mechanism in algal systems.

In mixed open cultures, microalgae species composition is affected by the nitrogen to phosphorus (N/P) ratio. Phosphorus removal in mixed cultures is mainly achieved through assimilation into algal cells.[33,60] Microalgae can also store excess nutrients for use during nutrient-limitation periods, enhancing their adaptability to changing environmental conditions.[6] Nitrates are stored in vacuole,[130] while phosphorus is taken up as inorganic phosphate and stored as polyphosphate granules.[136,137] Phosphorus removal is also facilitated by increasing the pH above 9.[33] Nutrient uptake depends on algal biomass concentration, and phosphorus removal is generally lower than nitrogen due to the higher nitrogen content in algal biomass,[123,138] as it illustrated the boxplot (Fig. 2a).

Beyond nutrient removal efficiency, the reproducibility and reusability of microalgae-based systems in water purification are critical for their large-scale application.[139] The efficiency of pollutant removal, including nutrients and organic matter, may vary due to environmental fluctuations such as temperature, light intensity, and wastewater composition, affecting process reproducibility.[33] In addition, the stability of algal–bacterial consortia play a key role in maintaining consistent purification performance over time. Microalgal biomass can be reused across successive treatment cycles, contributing to resource recovery and process sustainability; however, challenges such as contamination, shifts in microbial community structure, and reduced metabolic activity may limit long-term purification efficiency.[139] Therefore, ensuring stable operational conditions and effective biomass management is essential for achieving reliable and water purification performance.

Microalgae biomass

Biomass harvesting

The harvesting process involves the separation of microalgae biomass from the cultivation medium and accounts for 20 to 30% of the total algal production cost.[140,141] Various methods that have been reported in the literature, including physical, chemical, biological, electrical, and magnetic particle-mediated separation.[107,142] Physical methods include centrifugation, gravity sedimentation, filtration, and flotation. Chemical methods involve flocculation using inorganic and organic compounds. Centrifugation is the primary harvesting method for pilot-scale systems.[10,43] Biological methods such as autoflocculation and bioflocculation are employed to increase biomass density and facilitate settling.[107,142] Autofloculation *via* magnesium hydroxide precipitation (80 g L^{-1} $MgCl_2 \cdot 6H_2O$, to 33 m^3 raceway system)[87] was highly effective, achieving 92% reduction in turbidity. At the same time, ammonia and phosphorus removal reached 32 and 91%, respectively. Electropreciflocculation combined with filter press yielded harvesting efficiencies of about 98.24% in a 120 m^2 area raceway pond, with as cost of \$3.46 kg^{-1} of dry algal biomass.[5] The use of "water-net algae" such as *Hydrodictyon reticulatum* was proposed to enhance harvesting efficiency.[76]

The cost of harvesting algal biomass at a concentration 200 mg L^{-1} using cotton filters was estimated at 0.15 ₤ per m^2 filter area per kg biomass.[143] Using commercial grade ferrous sulfate, harvesting cost ranged from 0.17 to 0.3 USD per kg biomass, significantly lower than those using analytical grade ferrous sulfate.[144] Fasaei *et al.* (2018)[145] conducted a comparative cost analysis of flocculation, membrane and vacuum filtration. Flocculation was the most economical (0.30 € per kg of dry algal biomass), followed by vacuum filtration (0.80 € per kg of dry algal biomass) and membrane filtration (1.10 € per kg of dry algal biomass).

Biomass utilization

Microalgae biomass produced during wastewater treatment has diverse applications, making it a sustainable resource for environmental and industrial use. The reuse of algal biomass in order to improve water quality and sustainable ecosystem.[139] Common proposed uses include biofuel and biochar production, as well as fertilizers.[24,64,65,90] Microalgal biochar is an effective sorbent for removing various pollutants from effluents.[146] The produced biochar, can also be used for carbon sequestration, soil improvement, wastewater treatment, and as a precursor for nanoparticle synthesis.[147] These downstream operations highlight the role of algal biomass in promoting circular economy and sustainable biorefinery processes.[147]

Algal biomass is used in fertilizer production due to its content of nitrogen, phosphorus, and potassium, essential nutrients for plant growth. This practice helps to promote sustainable agriculture by recycling nutrients from wastewater.[148,149] Another important application is in animal feed, where protein-rich biomass serves as a sustainable alternative to conventional feedstocks like fishmeal, especially in aquaculture and livestock farming.[148] The protein and carbohydrate content of algal biomass varies depending on species and cultivation conditions.[14,111]

Microalgae are also used for biodiesel production due to their high lipid content, particularly species like *Chlorella vulgaris* and *Nannochloropsis*.[149] The examination of nutrient removal with *Hydrodictyon reticulatum* from secondary-treated wastewater and further bioethanol production from the harvested biomass.[76] One- and two-step transesterification methods were tested for *Chlorococcum* sp. and *Scenedesmus* sp. cultivated in secondary-treated municipal wastewater and in modified BG-11 medium, respectively. While *Chlorococcum* sp. showed no significant difference between methods, *Scenedesmus* sp. yielded 2.3 times more lipids using the two-step method.[15]

Microalgae are also utilized in the production of bioplastics and biochemicals, providing biodegradable alternatives to petrochemical-derived materials.[147] Furthermore microalgae, are used in pharmaceutical sector, offering bioactive compounds like omega-3 fatty acids, antioxidants, and pigments.[148,149] In addition, microalgae inoculums have been applied in cosmetic formulations for water body treatments.

Comparison with other systems

The comparison of activated sludge system with HRAPs, concluded that HRAPs were more effective in biomass production and nitrogen recovery, while also requiring less energy.[84] However, HRAPs require large surface area, they can operate in temperate climates without CO_2 addition achieved an annual average biomass productivity of 8 g m^{-2} d^{-1} (VSS), which is 2 to 3 times higher than that of conventional facultative ponds.[64] HRAPs are efficient in biomass production and nutrients removal with relatively low operational costs.[21] However, land and lining costs account for nearly 98% of the total cost; 48% for land and 50% for lining.[150]

The daily biomass production in photobioreactors was higher by 51% compared to HRAPs, although ammonia nitrogen removal was similar in both systems using mixotrophic algal–bacteria consortia.[80] Regarding environmental sustainability, HRAPs generally exhibit a lower carbon footprint compared to PBRs, due to reduced energy requirements for aeration and temperature control. However, PBRs offer superior process stability, which is often a trade-off for their higher operational costs, energy demand, carbon emissions and environmental footprints.[39] In raceway systems, gas flow delivery exhibited nearly double the transfer rate compared to air bubbling, offering a significant reduction in carbonation costs.[81]

Comparing WSPs and HRAPs for wastewater treatment reveals differences in cost, performance, and overall efficiency. The land area requirements ranges from 0.8 to 2.3 m^2 per capita for both systems.[150] Initial setup costs are 10 to 20 USD per m^3 d^{-1} for both WSPs and HRAPs, depending on the material, design and the type of infrastructures used.[150] WSPs and HRAPs have been adopted in low-income, rural or underdeveloped areas.[151] HRAPs are engineered for high algal productivity up to three times greater than WSPs,[21] which is critical for nutrient removal and energy recovery. WSPs are among the most economical low-maintenance systems, relying on natural processes without energy input. Their capital expenditure is low, ranging from 3 to \$7 m^{-3} per year, but they require more land, around 4 m^2 per capita.[152] HRAPs, in contrast, are significantly more efficient in nutrient removal, particularly nitrogen and phosphorus, due to their dense algal biomass.[153] Nutrient removal rates in HRAPs can exceed 90%, while WSPs typically achieve 50 to 70% removal, and require longer retention times for effective treatment.[64,154] It should be mentioned that, WSPs typically operate at HRTs ranging from 10 to 40 days, which is significantly higher than the HRT reported for the HRAP systems (Fig. 1). This variation is heavily influenced by seasonal climatic conditions and operational requirements. Most studies report lower values of HRT in HRAPs systems due to mechanical mixing and optimized design.[145]

Comparing algal–bacterial consortia with activated sludge systems, higher COD and nutrient removal were observed in HRAPs under limiting aeration (from 0 to 0.33 L min^{-1} L^{-1} reactor), demanded lower energy.[105] Also, algal–bacterial consortia can capture CO_2, unlike activated sludge systems, which emit significant amounts of CO_2.[18]

The integration of HRAPs with constructed wetlands is proposed as a robust hybrid treatment approach. Wetlands can serve as a secondary polishing step, enhancing solids and nutrient removal and environmental biodiversity.[38] This synergy justifies their incorporation in long-term wastewater management strategies, as they complement the high-rate removal of HRAPs with low-maintenance biological filtration.[38]

Life cycle assessment (LCA) and circular economy principles are integral to evaluating these systems. Current evidence suggests that integrating HRAPs with resource recovery, such as biofuel production from harvested biomass, can significantly improve the techno-economic viability of the process.[90] From a techno-economic and techno-industrial perspective, the large-scale implementation of microalgae-based wastewater treatment systems remains a key challenge. Capital and operational costs are strongly influenced by factors such as land requirements, energy demand for mixing, and biomass harvesting, which can account for a significant portion of total process costs.[141,155] In addition, variability in wastewater composition and environmental conditions may affect process stability, introducing uncertainties in economic performance. Techno-industrial feasibility also depends on the integration of resource recovery pathways, such as biofuel, biochar, or fertilizer production, which can offset operational costs and enhance overall process sustainability. Therefore, optimizing system design, improving energy efficiency, and developing integrated biorefinery approaches are essential to advance the economic viability and industrial adoption of microalgae-based treatment technologies.[56]

Conclusions

High-rate algal pond systems are rapidly advancing and environmentally sustainable solutions for wastewater treatment. Algal–bacteria consortia can effectively remove nutrients from wastewater while simultaneously produce biomass that can be utilized for energy production. This work analyzes the design parameters and environmental conditions that affect algal biomass production and nutrient removal in raceway systems. Optimal depth ranges from 20 to 40 cm, with the ideal N : P ratio for municipal wastewater is below 13. The applied HRT is affected by environmental conditions, with shorter HRTs (ranging from 7 to 1 d) observed at higher temperatures. Detailed analysis of nutrient removal mechanisms provides deeper insight into microalgal performance and system efficiency. Microalgal biomass represent a promising resource for future energy applications. Compared to other algal cultivation systems, HRAPs, demonstrate superior effectiveness in both nutrient removal and biomass production. Future recommendations for raceway systems include:

• Effect of operational and environmental conditions on dominant microalgae species.

• Implementation of real-time monitoring to improve operational efficiency and cost reduction. This approach will further elucidate the mechanisms of algal growth and nutrient removal.

• Solar energy integration to minimize energy needs and boost sustainability.

• Development of hybrid systems with wetlands or floating wetlands to increase overall productivity.

Author contributions

Styliani E. Biliani: investigation, writing – original draft preparation. Ioannis D. Manariotis: conceptualization, supervision, writing – reviewing and editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data are available upon request.

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