Real–world considerations on algae biochar

Josef Maroušek*, Prakash Bajagain

Technical University of Košice, Faculty of Mining, Ecology, Process Control and Geotechnologies (Letná 1/9, Košice–Sever, 042 00, Slovak Republic)

* = corresponding author (josef.marousek@gmail.com, +420 777 987 683)

Abstract

Algae–derived biochar has gained interest because of its distinctive physicochemical characteristics, particularly its high porosity and substantial content of macro– and micronutrients. However, much of the published literature remains overly optimistic, often neglecting the economic realities of large–scale implementation. This review critically synthesizes research mainly from the past decades to evaluate the progress, challenges, and prospects of algae–derived biochar. The principal achievement has been the translation of biological knowledge into increasingly efficient mass–cultivation systems, particularly those integrated with nutrient recovery. The major bottleneck remains algae harvesting, as even the latest technologies require substantial material and energy inputs, limiting economic viability. Emerging trends include the use of precipitation–based harvesting strategies to reduce biomass recovery costs and the subsequent thermochemical conversion of algal biomass into functionalized biochar products. Future progress will depend on prioritizing techno–economic feasibility, resource efficiency, and real–world scalability alongside improvements in biochar functionality and environmental performance.

Keywords

algae; biochar; pyrolysis; sustainability; circular bioeconomy

1.1 Introduction

To meet the needs of a growing population, agricultural production has intensified, making agriculture responsible for approximately one–third of global GHG emissions, mainly through methane (CH_4) and nitrous oxide (N_2O) released from farming activities (Sharma et al., 2026). Algae are among the most efficient photosynthetic organisms on Earth and exhibit diverse metabolic strategies, including photoautotrophy, heterotrophy, mixotrophy, and photoheterotrophy (Khoo et al., 2023). Owing to their rapid growth and high carbon fixation capacity, many algal species can capture CO_2 at rates substantially higher than those of

Accepted Manuscript

terrestrial plants, with some studies reporting values up to 50–fold greater under specific cultivation conditions (Ighalo et al., 2022). In addition, algal biomass is rich in valuable compounds, including pigments, polysaccharides, lipids, secondary metabolites, and various bioactive substances such as phenols, aldehydes, ketones, carboxylic acids, and their derivatives, making algae an attractive feedstock for a wide range of biotechnological applications (Anto et al., 2021).

On the other hand, lignocellulosic biomass, the most abundant renewable feedstock on Earth, possesses considerable potential to produce value–added products; however, in practice, it is still used predominantly for energy generation (Segers et al., 2024). In this context, algae have emerged as an alternative feedstock for biochar production especially in the context of wastewater management. Low production costs are often presented as a key benefit of algae biochar; however, this assumption is rarely supported by comprehensive economic assessments (Tan et al., 2023). Owing to their distinct biochemical composition and thermochemical characteristics, dried algal feedstocks can often be converted into biochar more efficiently than conventional lignocellulosic materials (Singh et al., 2021). Nevertheless, the cost of producing or procuring dried algal phytomass is often neglected (Figure 1) in academic studies (Afshar et al. 2024). The porous structure of biochar has been widely shown to improve soil physical, chemical, and biological properties, enhancing soil fertility, water retention, nutrient availability, and microbial activity (Ali et al., 2025). Owing to its stability and adsorption capacity, biochar also promotes carbon sequestration and pollutant immobilization, thereby reducing environmental impacts and fertilizer requirements while supporting more sustainable agricultural production (Omokaro et al., 2025).

In contrast to biochars produced from terrestrial phytomass (e.g., digestate, crop residues, and spent grains) and waste–derived feedstocks (e.g., food–processing residues, sewage sludge, and waste paper), which have been investigated in agricultural applications for decades and are increasingly recognized by farmers (Vochozka et al., 2016; Strunecký et al., 2025), evidence from large–scale field trials of algae–derived biochar remains extremely limited in the published literature (Campion et al. 2023). While algae–derived biochar is often promoted as an ESG–relevant solution owing to its potential benefits for carbon sequestration, wastewater management, and circular bioeconomy strategies, published studies provide contradictory conclusions regarding its environmental impacts, largely because the energy demand associated with algae harvesting, dewatering, drying, and conversion can be substantial (Braud et al. 2025).

Accepted Manuscript

The same factors have also contributed to inconsistent conclusions in techno– economic assessments of the process (Parthipan et al. 2026).

This review is especially timely given the increasing promotion of algae–derived biochar as a sustainable solution despite substantial uncertainties regarding its scalability, techno–economic feasibility, and net environmental benefits.

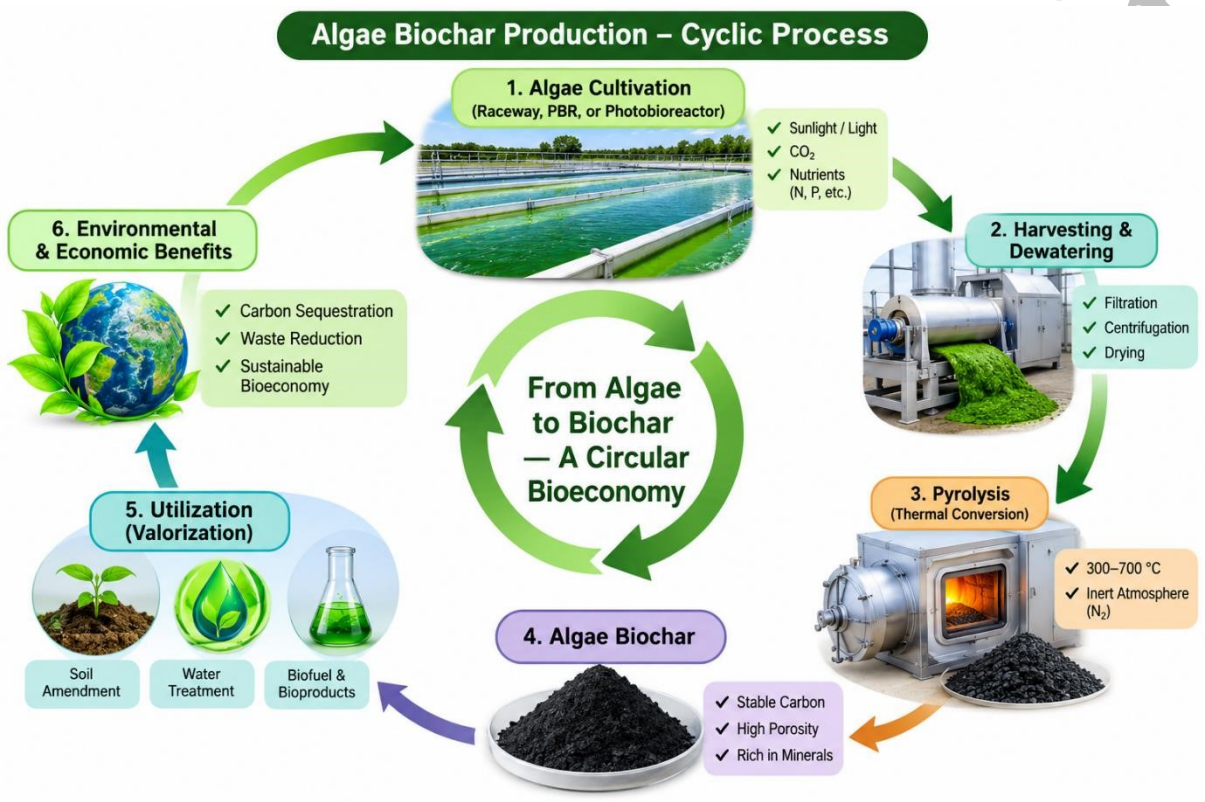


Figure 1: Visualizations of algal biochar production, as commonly presented in many scientific publications, tend to largely overlook the technical challenges associated with harvesting algal biomass and the energy requirements of its subsequent processing.

1.2 GHG phenomena

Agricultural intensification has increased the demand for sustainable approaches to soil management, nutrient utilization, and greenhouse gas (GHG) mitigation. Agriculture contributes substantially to global anthropogenic GHG emissions, particularly through methane (CH_4) and nitrous oxide (N_2O) released from livestock production, fertilizer application, and soil management (Sharma et al., 2026). Consequently, developing alternative materials that improve soil fertility, enhance nutrient-use efficiency, and contribute to carbon management has become increasingly important.

Accepted

In this context, algae-derived biochar represents a promising multifunctional material linking wastewater treatment, biomass valorization, and agricultural applications. Algae can utilize dissolved nutrients from wastewater and assimilate CO_2 during cultivation, producing biomass that can subsequently be converted into biochar through thermochemical processing. Depending on its production conditions and physicochemical characteristics, the resulting biochar may improve soil properties, retain nutrients, immobilize potentially toxic metals, and contribute to longer-term carbon storage. However, these potential benefits must be evaluated against the energy and material requirements associated with cultivation, harvesting, dewatering, drying, and thermochemical conversion. Therefore, the sustainability of algaederived biochar depends not only on its functional properties but also on the environmental and economic performance of the complete production pathway.

1.3 Research gap and novelty

Despite increasing research interest in algae-derived biochar, several important knowledge gaps remain. Existing reviews have predominantly examined algal biochar production, physicochemical characterization, wastewater treatment, or environmental applications as relatively independent research topics. Consequently, insufficient attention has been given to the interdependence between cultivation conditions, wastewater composition, biomass recovery, feedstock characteristics, thermochemical conversion, and the final functional performance of the resulting biochar. Furthermore, the environmental and economic advantages of algae-derived biochar remain uncertain because harvesting, dewatering, and drying can impose substantial energy requirements, while wastewater-grown biomass may accumulate potentially hazardous contaminants.

The present review addresses these limitations through an integrated and critical evaluation of the complete algae-to-biochar production pathway. Unlike reviews focusing predominantly on biochar preparation or adsorption applications, this work connects upstream biomass production with downstream processing, life-cycle environmental performance, technoeconomic feasibility, and practical environmental applications. Particular attention is given to comparative evidence on biomass productivity, nutrient removal, harvesting efficiency, biochar yield, environmental hotspots, and contaminant fate. The review also identifies limitations in industrial-scale validation, long-term field performance, and standardized environmental assessment. By integrating these aspects, this review aims to establish a more realistic

Accepted Manuscript

understanding of the opportunities and constraints associated with the commercial and environmental deployment of algae-derived biochar.

2. Algal Biomass Production, Downstream Processing, and Biochar Valorization

2.1. Algal cultivation and wastewater integration

Algal cultivation represents the upstream stage of algae-derived biochar production and determines the quantity, biochemical composition, and physicochemical quality of the biomass available for subsequent processing. Cultivation systems may utilize synthetic nutrient media, municipal wastewater, industrial wastewater, agricultural effluents, or combinations of wastederived nutrient sources. Wastewater-integrated cultivation is particularly attractive because dissolved nitrogen and phosphorus can support algal growth while simultaneously reducing the nutrient load of the wastewater.

However, cultivation performance is strongly influenced by wastewater composition, including nitrogen and phosphorus concentrations, organic matter content, chemical oxygen demand (COD), pH, salinity, and the presence of potentially toxic contaminants. Nutrient availability alone does not determine biomass productivity, since light availability, temperature, hydraulic retention time, algal species, and cultivation configuration also influence growth. Consequently, biomass productivity and nutrient removal should be evaluated together rather than treating wastewater treatment as an automatic consequence of algal cultivation.

Wastewater-derived biomass also differs from biomass produced in synthetic media in terms of biochemical composition and potential contaminant accumulation. These differences can influence subsequent biochar yield, ash content, elemental composition, and environmental safety. Therefore, cultivation optimization should consider not only biomass production and nutrient removal but also the suitability of the recovered biomass for thermochemical conversion and its intended final application.

Algae are highly productive photosynthetic organisms that support carbon capture, bioenergy generation, and environmental remediation, making them attractive feedstocks for circular bioeconomy applications. Recent studies have taken a more realistic perspective by exploring economically viable synergies between wastewater treatment, algal cultivation, and downstream biomass valorization. For example, recent experiments by Elango et al. (2026) demonstrated the cultivation of *Spirulina* in domestic wastewater, achieving a phytomass concentration of 0.83 g L^{-1} while generating feedstock for the subsequent production of phycocyanin (22.5 mg L^{-1}), polyhydroxyalkanoates (PHAs; confirmed by FTIR through

Accepted Manuscript

characteristic O–H, C–H, and C=O absorption bands), and biochar. The latter was produced by torrefaction at 250 °C, yielding 31% biochar with enhanced thermal stability and fixed–carbon content. Similarly, Hait et al. (2024) reported that *Marvania coccoides* cultivated in poultry litter and domestic wastewater supplemented with kinetin achieved a biomass productivity of 114.29 mg L^{-1} d^{-1} while removing up to 99% of ammonia and 95% of phosphate. Subsequent pyrolysis of the harvested biomass produced bio–oil and biochar, highlighting the feasibility of coupling wastewater treatment with biomass valorization and energy recovery. Gawali et al. (2025) and Roy et al. (2025) demonstrated the potential of wastewater–grown algae as feedstocks for integrated biorefineries. *Marvania coccoides*, cultivated with nutrient supplementation (N, Mg, and Fe) and scaled up to 200–L open raceway ponds, exhibited enhanced phytomass productivity, biochemical composition, and nutrient removal efficiency. Likewise, *Chlorella homosphaera* effectively removed nutrients, COD, and heavy metals from wastewater. Phytomass from both species was subsequently converted through pyrolysis and transesterification into bio–oil, biochar, and biodiesel. These findings suggest that nutrient– rich wastewater can improve phytomass quality and downstream biofuel yields, supporting the development of zero–waste biorefinery systems. Beyond biochar production itself, Aljaziri et al. (2026) demonstrated that chemical activation and nitrogen enrichment can substantially increase algae biochar surface area and adsorption capacity. Similar improvements could potentially be realized through the exfoliation of algae–derived biochar, although this approach remains largely unexplored (Marousek et al., 2025).

Furthermore, Xu et al. (2025) reported that biochar modified with MgFe–layered double hydroxides, a class of highly reactive lamellar metal hydroxides widely used for adsorption and nutrient capture, enhanced CO_2 fixation and nearly doubled the phytomass production of *Chlorella pyrenoidosa*. These findings suggest that algae–derived biochar can serve not only as a value–added product but also as a cultivation enhancer within algal production systems. Collectively, these studies indicate that biochar may function not only as a carbon–rich energy material but also as a process intensifier in algae cultivation and wastewater remediation, contributing to the development of more efficient circular bioeconomy systems. Beyond wastewater utilization, agricultural residues have also been integrated into algal cultivation systems. Song et al. (2026) demonstrated that corn cob hydrolysate improved algal biomass productivity while enhancing nutrient removal efficiency.

Accepted Manuscript

2.2. Biomass harvesting, dewatering, and drying

Following cultivation, algal biomass must be recovered from the liquid medium before thermochemical conversion. Biomass harvesting, dewatering, and drying represent distinct downstream operations and should not be considered interchangeable. Harvesting involves separating algal cells from the cultivation medium, whereas dewatering further increases the solids concentration by removing interstitial water. Drying subsequently reduces the remaining moisture content to a level appropriate for the selected thermochemical conversion process.

Centrifugation, chemical flocculation, bioflocculation, dissolved-air flotation, filtration, and magnetic separation are among the principal techniques used for algal biomass recovery. Their suitability depends on algal cell size, surface characteristics, culture density, wastewater composition, and the required biomass concentration. Although centrifugation can achieve efficient separation, its electricity requirements and capital costs may restrict large-scale implementation. Chemical flocculation can reduce energy consumption but may introduce residual chemicals that affect downstream processing and product quality.

Alternative methods, including bioflocculation and flotation, have attracted attention because they may reduce chemical consumption and operational costs. Wen et al. (2021), for example, developed a buoy-bead flotation approach using sodium borosilicate microspheres coated with Moringa oleifera extracts. The system achieved a harvesting efficiency of 89.1% at neutral pH using an optimal microsphere dosage of 0.7 g L^{-1}. However, its final biomass concentration, energy consumption, and performance under large-scale wastewater conditions require further evaluation.

Magnetic separation also offers opportunities for improving biomass recovery. Fu et al. (2025) applied an Extreme Gradient Boosting model to predict harvesting efficiency in magnetic nanoparticle-assisted systems, reporting a coefficient of determination (R^2) of 0.932. Nevertheless, predictive accuracy should not be interpreted as experimentally demonstrated harvesting efficiency. Practical implementation requires validation using continuous cultivation systems and realistic wastewater matrices.

Following harvesting, dewatering and drying become particularly important because the high moisture content of algal biomass increases the thermal energy required for subsequent conversion. Mechanical dewatering can reduce the water load before thermal drying, whereas waste heat integration and solar-assisted drying may offer opportunities to reduce energy demand. Accordingly, harvesting technology should be selected based on its overall

Accepted Manuscript

contribution to biomass recovery cost, final solids concentration, energy consumption, chemical requirements, and compatibility with the intended thermochemical conversion process.

Algal phytomass harvesting remains a major bottleneck, as conventional methods are often energy– and chemical–intensive, prompting the development of more sustainable bio–based alternatives. For example, Wen et al. (2021) reported a buoy–bead flotation system based on sodium borosilicate microspheres coated with *Moringa oleifera* extracts, achieving a harvesting efficiency of 89.1% at neutral pH with an optimal dosage of 0.7 g L^{-1}. The authors attributed phytomass separation to enhanced hydrophobic interactions and reduced electrostatic repulsion between algal cells and the modified microspheres, leading to effective floc formation without conventional chemical flocculants. While this approach may offer environmental advantages over centrifugation and synthetic–flocculant–based harvesting, its large–scale economic feasibility and operational performance under variable wastewater conditions remain insufficiently demonstrated. Complementing these developments, Fu et al. (2025) employed an Extreme Gradient Boosting machine–learning model to optimize harvesting systems based on magnetic nanoparticles, achieving a high predictive accuracy (R^2 = 0.932). While the study highlights the growing potential of artificial intelligence for improving harvesting efficiency, selecting suitable algal strains, and guiding nanoparticle design, its findings remain largely predictive and require validation under real–world operating conditions. As with many data–driven approaches, practical applicability will ultimately depend on the availability of robust datasets and successful scale–up beyond laboratory environments.

Although conventional pyrolysis remains the dominant route for converting algal phytomass into bio–oil and biochar, many reported studies focus primarily on product yields rather than process economics, energy balances, or industrial scalability. Consequently, more efficient thermochemical approaches, such as microwave–assisted catalytic cracking, are attracting increasing attention. For example, Gawali et al. (2025) reported biochar and bio–oil yields of up to 57% and 27%, respectively, from residual algal phytomass pyrolyzed at 550 °C for 60 minutes. Similarly, Roy et al. (2025) observed bio–oil yields of up to 36 wt% at 500 °C, whereas biochar yields declined with increasing temperature, reaching 64 wt% at 400 °C. Beyond biofuel production, algae–derived biochars have demonstrated broader environmental applications. Myung et al. (2024) showed that biochar produced from *Spirulina* at 600 °C effectively immobilized Pb and Zn in contaminated soils. Likewise, Bhowmick et al. (2022) found that biochars derived from algal and woody biomass and subsequently activated with H_2O_2 exhibited increased surface area and a higher abundance of oxygen–containing functional groups,

Accepted Manuscript

resulting in enhanced adsorption performance. Collectively, these studies highlight the versatility of algae–derived biochar; however, evidence supporting the technical and economic feasibility of large–scale deployment remains limited (Figure 2).

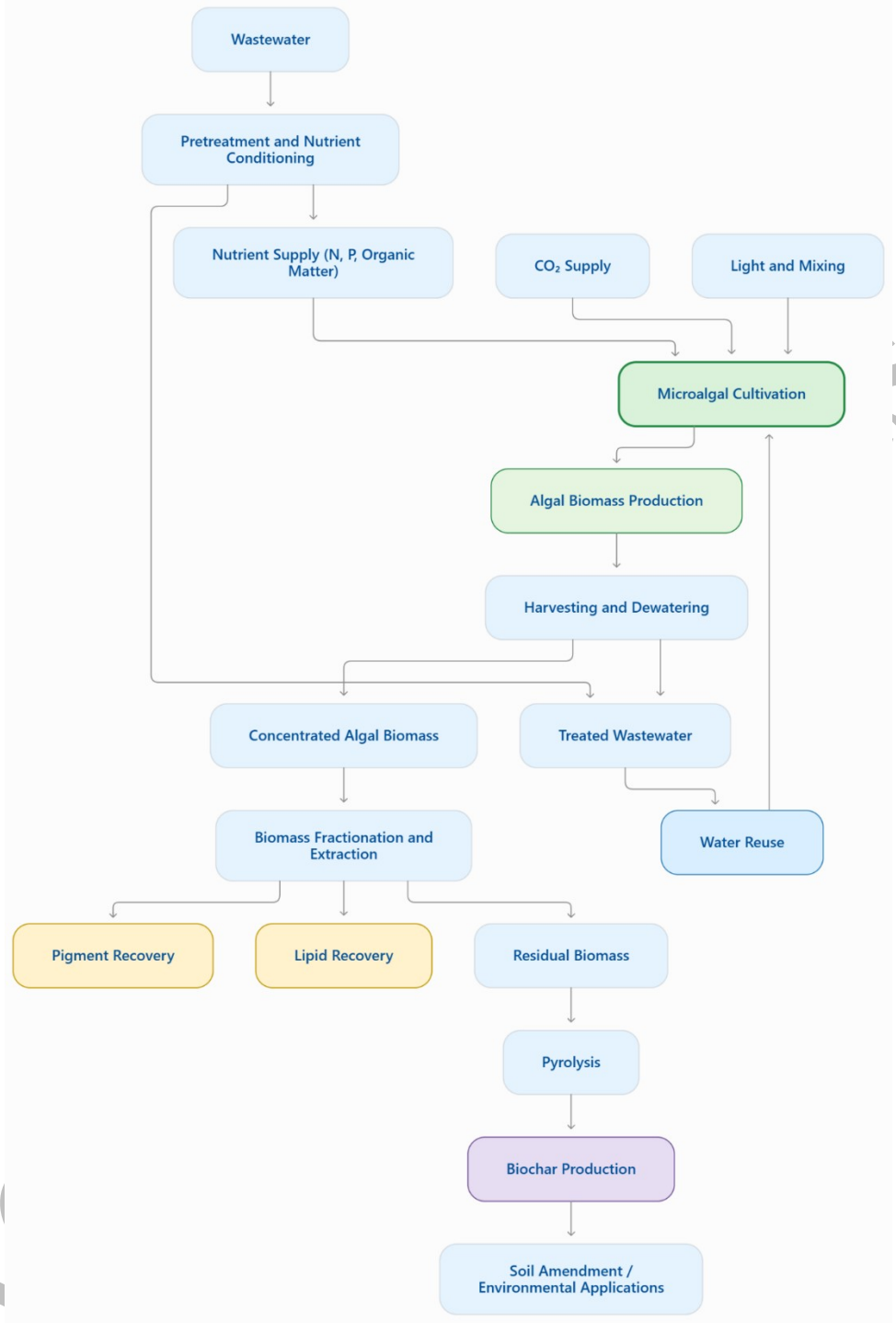


Figure 2: Conceptual flow diagram of microalgae valorisation, including residual biomass conversion into biochar.

The effectiveness of biochar is commonly attributed to its ability to modify soil properties, including increases in soil pH, electrical conductivity, and dissolved soil organic carbon, as well as its capacity to immobilize heavy metals through electrostatic attraction, ion exchange, surface complexation, and precipitation processes (Marousek et al., 2026). However, the extent and persistence of these effects remain highly dependent on feedstock characteristics, production conditions, and site–specific environmental factors. Recent studies have also explored microwave–assisted catalytic cracking as an alternative to conventional pyrolysis. Thanaraj et al. (2025) reported bio–oil yields of up to 58% and biochar yields of up to 65%, accompanied by improved energy efficiency under optimized operating conditions. Similarly, Wang et al. (2026) achieved a bio–oil yield of 56 wt% from greywater–grown algae using microwave pyrolysis, with process parameters optimized through response surface methodology and machine–learning models. While these results demonstrate the technical potential of advanced thermochemical conversion technologies, their practical significance remains uncertain. High nitrogen content in algal bio–oils, the need for extensive upgrading, catalyst costs, and the energy requirements of microwave–based systems continue to pose significant barriers to commercial–scale implementation.

2.3 Thermochemical conversion and biochar yield

Thermochemical conversion represents the principal downstream transformation step in algaederived biochar production. The selected conversion technology and operating conditions influence the distribution of solid, liquid, and gaseous products, as well as the physicochemical characteristics of the resulting biochar. Conventional pyrolysis, microwave-assisted pyrolysis, torrefaction, and hydrothermal processes have been investigated for algal biomass valorization. However, their products and operating requirements differ and should be evaluated separately. Conventional pyrolysis involves thermal decomposition of biomass under oxygen-limited or oxygen-free conditions. Temperature, residence time, heating rate, and feedstock composition are major factors determining biochar yield and properties. Increasing pyrolysis temperature generally promotes devolatilization and carbonization, often reducing solid yield while modifying fixed-carbon content, aromaticity, porosity, and surface functional groups. However, the relationship between temperature and biochar properties is feedstock-dependent because algal biomass contains substantial amounts of proteins, lipids, carbohydrates, and inorganic constituents.

Accepted Manuscript

The study by Gawali et al. (2025) reported biochar and bio-oil yields of up to 57% and 27%, respectively, from residual algal phytomass pyrolyzed at 550 °C for 60 min. Roy et al. (2025) reported a maximum bio-oil yield of 36 wt% at 500 °C, while the biochar yield reached 64 wt% at 400 °C. The reduction in biochar yield with increasing temperature illustrates the influence of operating conditions on product distribution. These results should nevertheless be interpreted in relation to differences in feedstock composition, reactor configuration, and yield determination methods.

Torrefaction offers a lower-temperature alternative to conventional pyrolysis. Elango et al. (2026) reported a biochar yield of 31% from Spirulina processed at 250 °C, demonstrating the potential for producing a thermally stable carbon-rich solid while retaining a substantial fraction of the original biomass. Nevertheless, torrefaction products should be distinguished from conventional high-temperature pyrolysis biochars because their chemical composition and degree of carbonization may differ.

Microwave-assisted catalytic conversion has also attracted attention as an alternative approach. Thanaraj et al. (2025) reported bio-oil and biochar yields of up to 58% and 65%, respectively, under optimized microwave-assisted catalytic cracking conditions. Wang et al. (2026) reported a bio-oil yield of 56 wt% from greywater-grown algae using microwave pyrolysis. However, the energy requirements of microwave systems, catalyst consumption, and the need for bio-oil upgrading remain important considerations for commercial implementation.

Hydrothermal processes should also be distinguished from dry pyrolysis. Hydrothermal carbonization and hydrothermal liquefaction operate in water-containing systems and produce different product distributions. Hydrothermal liquefaction is primarily directed towards biocrude production and should not be treated as equivalent to a process specifically optimized for biochar production.

Overall, the reported biochar yields demonstrate considerable variation across algal species and conversion conditions. However, direct comparison requires consistent reporting of feedstock moisture content, dry-basis yield, ash content, reactor conditions, and product characterization. Future studies should therefore report complete mass balances and energy balances to establish the actual efficiency and sustainability of algae-derived biochar production.

2.4. Biochar functionalization and product valorization

The physicochemical characteristics of algae-derived biochar can be further modified through chemical activation, mineral enrichment, nitrogen functionalization, and other

Accepted Manuscript

surfaceengineering approaches. These treatments aim to improve specific properties, including surface area, pore accessibility, surface charge, and the abundance of functional groups, thereby enhancing adsorption and nutrient-retention performance.

Aljaziri et al. (2026) demonstrated that chemical activation and nitrogen enrichment can improve the surface characteristics and adsorption capacity of algae-derived biochar. Similarly, Bhowmick et al. (2022) reported improved adsorption performance following H_2O_2 activation of algal and woody biomass-derived biochars, associated with increased surface area and oxygen-containing functional groups. Xu et al. (2025) further demonstrated the potential of MgFe-layered double hydroxide-modified biochar for improving CO_2 capture and microalgal cultivation performance.

Despite these advances, functionalization introduces additional processing requirements, including chemical consumption, washing, separation, and potentially increased energy demand. These factors may influence production costs and environmental performance. Moreover, the reuse, regeneration, and long-term stability of modified biochars require further investigation.

Beyond the production of biochar as an individual product, algae-based biorefineries provide opportunities for recovering pigments, lipids, proteins, and biopolymers before thermochemical conversion of residual biomass. This cascading utilization approach may improve the overall resource efficiency of algal cultivation by generating multiple products from a single biomass stream. However, the economic and environmental advantages depend on product recovery efficiencies, market demand, and the additional processing requirements associated with each valorization step.

3.1. Environmental considerations

Across the reviewed literature, Life Cycle Assessment (LCA) consistently indicates that algae–based systems have the potential to deliver substantial environmental benefits. However, the magnitude, reliability, and generalizability of these benefits remain highly sensitive to methodological choices, including system configuration, functional unit selection, allocation procedures, and system boundary definitions. Consequently, reported environmental advantages should be interpreted with caution, as variations in modelling assumptions can significantly influence outcomes. Using an ISO 14040–compliant LCA framework, Sun et al. (2024) evaluated the environmental performance of wastewater–derived algae systems and identified process energy demand as the dominant environmental hotspot. Specifically, the

Accepted Manuscript

leaching–activation pathway and the energy requirements associated with pyrolysis and activation contributed up to 95.3% of total environmental impacts, highlighting the strong dependence of system sustainability on energy–intensive processing steps. While the authors reported positive environmental outcomes, including reduced abiotic resource depletion and enhanced resource circularity, these findings are subject to several limitations. Most notably, the assessment did not account for downstream applications such as energy storage, potentially leading to an underestimation of broader system benefits. Conversely, the study's favourable conclusions may also be constrained by assumptions regarding energy sources and process efficiencies, which may not be representative of commercial–scale operations. This raises questions about the scalability and robustness of the reported environmental gains under real–world deployment conditions.

A key finding emerging from comparative assessments is that integrated valorization pathways generally outperform single–product systems across most environmental impact categories. For example, Mohit et al. (2024) reported that integrating biochar production into algal biofuel systems reduced global warming potential (GWP) by up to 23% while improving net energy recovery by 79%. Similarly, studies by Li et al. (2022) and Ryland et al. (2026) demonstrate that nutrient recovery through source–separated waste streams or wastewater–integrated cultivation can lower greenhouse gas (GHG) emissions and improve overall energy balances, typically achieving GWP reductions and energy surplus improvements in the range of 10–20%. However, these reported benefits should be interpreted with caution. The environmental performance of nutrient–recovery systems is highly dependent on local wastewater characteristics, nutrient availability, treatment infrastructure, and operational reliability. Consequently, wastewater–based cultivation cannot be regarded as a universally superior solution; rather, its advantages are strongly context–specific and may diminish under less favorable operating conditions.

Within thermochemical conversion pathways, hydrothermal liquefaction systems (Karimi and Simsek, 2025; Ryland et al., 2026) consistently demonstrate lower life–cycle emissions than fossil diesel and many conventional biodiesel pathways. Nevertheless, these advantages are partially offset by the substantial energy demands associated with upstream processing, particularly biomass harvesting and dewatering. This highlights a persistent limitation within hydrothermal liquefaction systems: while conversion efficiencies are often high, the environmental burden remains concentrated in pre–treatment stages, thereby constraining overall sustainability gains. Additional comparative studies by Bhowmick et al. (2022) and Cole

Accepted Manuscript

et al. (2023) indicate that algae–derived biochar systems can achieve net–negative carbon emissions, with estimated CO_2 sequestration costs ranging from USD 702 to 1,585 per ton of CO_2. Although these findings support the carbon–removal potential of biochar pathways, they also reveal important trade–offs. Environmental burdens are not eliminated but rather shifted towards capital–intensive infrastructure, pyrolysis operations, and long–term carbon storage requirements. Furthermore, the relatively high sequestration costs raise questions regarding the economic viability and scalability of such systems compared with existing carbon mitigation strategies (Mardoyan and Braun, 2015).

Finally, large–scale system integration analyses, such as Zhang et al. (2026), suggest that indirect substitution effects (such as replacing imported soybean products with algal phytomass) may contribute more substantially to climate benefits than direct biological carbon fixation. This finding exposes a critical methodological challenge within LCA studies. Reported environmental outcomes are highly sensitive to assumptions regarding system expansion, avoided products, and substitution credits. As a result, conclusions regarding the carbon neutrality or carbon negativity of algae–based systems can vary considerably depending on modelling choices, reducing the comparability of studies and introducing substantial uncertainty into environmental sustainability claims (Table 1).

Parameter	**Comparative characteristics / reported values**	**References**
Algal feedstock	Spirulina (Arthrospira platensis), Chlorella sp., Chlorella vulgaris, Scenedesmus quadricauda, Nannochloropsis sp., Chlamydomonas reinhardtii, Isochrysis galbana and mixed algal biomass.	Yu et al. (2017); Mustapha et al. (2025)
Biomass origin	Cultivated microalgal biomass, wastewater-grown algae, residual biomass after lipid or pigment extraction, and waste algal biomass.	Mustapha et al. (2025); Show et al. (2024)
Conversion technology	Conventional pyrolysis, microwave-assisted pyrolysis, hydrothermal carbonization (HTC) and torrefaction.	Show et al. (2024); Mustapha et al. (2025)

Accepted Manuscript

Pyrolysis temperature	Commonly 350–900°C, depending on feedstock and desired biochar characteristics. Examples include 400–900°C for Chlorella sp., 400–600°C for Spirulina sp. and 750°C for Scenedesmus quadricauda.	Yu et al. (2017); Mustapha et al. (2025); Chlorella study (2024)
Residence time	Reported experimental conditions include 20, 45 and 60 min; some studies use longer treatment periods.	Yu et al. (2017); Mustapha et al. (2025)
Biochar yield	Approximately 20–48.3% across selected microalgal feedstocks and production conditions. Chlorella sp.: 21.9–38.4% at 400–900°C; Arthrospira platensis: 25–31% in reported studies.	Yu et al. (2017); Mustapha et al. (2025); Chlorella study (2024)

403

Accepted Manuscript

Carbon content	Approximately 50–60 wt% reported for Chlorella sp. biochar produced at 600–900°C. Carbon content generally increases with increasing pyrolysis temperature.	Chlorella study (2024)
Nitrogen content	Nitrogen-containing compounds are characteristic of protein-rich algal feedstocks. Nitrogen retention and loss depend on pyrolysis temperature and processing conditions. A universal numerical range is not established by the cited comparative studies.	Mustapha et al. (2025); Nawaz et al. (2024)
Phosphorus content	Phosphorus may be retained in the mineral-rich ash fraction, depending on the original algal biomass and pyrolysis conditions. Quantitative values require feedstock-specific elemental analysis.	Show et al. (026) Kim et al. (
BET surface area	Unmodified biochars: approximately 2.12–35.66 m^2/g in selected studies. Chlorella sp.: 4.05–6.16 m^2/g; Spirulina sp.: 6.46–7.89 m^2/g in selected temperature-dependent experiments.	Mustapha et al. (2025)
BET surface area after activation	KOH-activated Chlorella and Spirulina biochars reached 422.6 and 404.8 m^2/g, respectively, following combined urea and KOH modification.	Mustapha et al. (2025)
Pore structure	Micro-, meso- and macroporous structures can occur. Pore volume and diameter depend on feedstock, pyrolysis temperature and chemical activation.	Mustapha et al. (2025)
Surface functional groups	–OH, –COOH, C=O, C–O, $–NH_2$ and nitrogen-containing surface groups have been reported. Their abundance generally changes with pyrolysis temperature.	Chlorella study (2024); Kim et al. (2026)
Aromaticity and carbon stability	Increasing pyrolysis temperature promotes carbonization and aromatic structures while reducing H/C and O/C ratios. For Chlorella biochar produced at 600–900°C, H/C was reported at ≤0.32.	Chlorella study (2024); Mustapha et al. (2025)

Accepted Manuscript

Table 1. Feedstock, production conditions and physicochemical characteristics of algaederived biochar.

Life Cycle Assessment (LCA) provides a systematic framework for evaluating the environmental performance of algae-derived biochar production, from biomass cultivation to final product utilization. However, comparisons between published assessments are complicated by differences in system boundaries, functional units, feedstock origins, conversion technologies, and carbon accounting approaches. For example, Sun et al. (2024) investigated the valorization of wastewater-derived microalgae through phosphorus recovery and biochar production for electrochemical applications. The study identified the energy requirements associated with processing, leaching, and activation as major contributors to environmental impacts. Mohit et al. (2024) evaluated biofuel production from microalgae cultivated in greywater and demonstrated the environmental and economic importance of integrating wastewater treatment with biomass valorization. Similarly, Li et al. (2022) investigated source-separated wastewater-integrated microalgae biofuel production and highlighted the importance of nutrient recovery in overall system performance.

Although these studies provide valuable information for understanding the sustainability of algal biorefineries, they do not all assess the same final product or production pathway. In particular, assessments of algal biofuel production should not be directly interpreted as LCA results for algae-derived biochar. Their relevance lies primarily in identifying shared upstream environmental burdens, such as cultivation, harvesting, dewatering, and energy consumption. The environmental performance of algae-derived biochar is also influenced by the accounting of biogenic carbon. Carbon assimilated during algal growth is not necessarily equivalent to permanently sequestered carbon. A credible carbon balance must consider the proportion of biomass carbon retained in biochar, its long-term stability, emissions during conversion, energy-related emissions, and the fate of the biochar after application. Avoided emissions and substitution credits should be reported separately to prevent overestimating the climate benefits of the system.

Therefore, future LCA studies should establish consistent functional units and transparent system boundaries, while incorporating realistic energy requirements and long-term carbonstorage assumptions. Particular attention should also be given to sensitivity analyses addressing electricity sources, biomass productivity, biochar yield, and alternative product allocation methods (Table 2).

Accepted Manuscript

438

Accepted Manuscript

LCA parameter	Aspects to be considered	Evidence and limitations in the reviewed literature
System boundaries	Cultivation, wastewater treatment, harvesting, dewatering, drying, conversion, and biochar utilization	Boundaries differ between individual studies; complete algae-to-biochar coverage is not consistently available
Functional units	1 kg dry algal biomass, 1 kg biochar, 1 m^3 wastewater treated, or a defined carbon-removal service	Different functional units prevent direct comparison
Energy sources	Grid electricity, renewable electricity, process heat, waste heat, and recovered energy	Energy assumptions strongly influence environmental performance
Feedstock origin	Synthetic-medium-grown algae, wastewater-grown algae, residual algal biomass, and mixed feedstocks	Wastewater integration may reduce synthetic nutrient requirements
Conversion technology	Pyrolysis, microwave-assisted pyrolysis, torrefaction, hydrothermal carbonization, and other conversion pathways	Different technologies generate different product distributions and energy requirements
Environmental hotspots	Cultivation, harvesting, dewatering, drying, pyrolysis, activation, and transportation	Sun et al. (2024) identified processing and activation energy as important impact contributors
Carbon accounting	Biogenic carbon uptake, biochar carbon retention, conversion emissions, avoided emissions, and substitution credits	Results depend on carbon allocation, biochar stability, and system-expansion assumptions
Main uncertainties	Biomass productivity, moisture content, electricity mix, conversion yield, product allocation, and carbon persistence	Limited industrial-scale data and inconsistent methodological assumptions constrain comparability

439 Table 2. Comparative methodological framework for life-cycle assessment of algae-derived 440 biochar and related algal biorefinery systems.

Accepted Manuscript

3.2. Contaminant fate during cultivation and thermochemical conversion

The environmental safety of algae-derived biochar depends not only on its adsorption properties but also on the fate of contaminants introduced during algal cultivation. This issue is particularly important when wastewater-grown biomass is used as a thermochemical feedstock. Algae can accumulate heavy metals, including Pb, Cd, Cu, Zn, and other potentially toxic elements, through adsorption onto cell surfaces and intracellular uptake. Organic contaminants may also associate with algal biomass depending on their chemical properties, biodegradability, and interactions with cellular components.

Although algal cultivation can contribute to wastewater remediation, the removal of contaminants from the aqueous phase does not necessarily represent their complete elimination. Instead, contaminants may be transferred from wastewater into the harvested biomass. Therefore, wastewater treatment efficiency should be evaluated together with the contaminant content and environmental suitability of the resulting biomass.

During thermochemical conversion, contaminant behavior depends on the chemical properties of individual elements and compounds and on the operating conditions. Heavy metals cannot be destroyed through conventional pyrolysis. They may become concentrated in the solid biochar because of organic matter loss, or they may be redistributed into condensable vapors and gaseous streams, depending on their volatility and chemical speciation. Consequently, total metal concentrations in biochar may increase even when the absolute mass of a particular metal is not retained completely in the solid fraction.

Organic contaminants may undergo thermal decomposition, volatilization, or chemical transformation during pyrolysis. However, complete destruction should not be assumed because some compounds or potentially hazardous transformation products may persist in the solid or liquid fractions. The extent of transformation depends on pyrolysis temperature, residence time, feedstock composition, and the chemical characteristics of the original contaminants. These considerations have important implications for the subsequent utilization of wastewater-derived algal biochar. Before agricultural application, biochar should be evaluated for total heavy-metal concentrations, metal leachability, potentially hazardous organic compounds, and ecotoxicological effects. In addition, a complete contaminant mass balance across the biochar, bio-oil, aqueous condensate, and gaseous fractions is necessary to determine whether thermochemical conversion achieves genuine contaminant stabilization or simply redistributes contaminants among different product streams. Accordingly, future

Accepted Manuscript

investigations should combine wastewater characterization, biomass contaminant analysis, thermochemical product characterization, leaching tests, and long-term soil monitoring. Such assessments are essential to ensure that the environmental benefits of wastewater-based algal cultivation are not offset by contaminant transfer during biochar production and application.

4.1 Techno–economic considerations

Techno–economic analyses consistently identify production costs of dried algae phytomass, system integration with wastewater treatment, and income from payments for carbon capture as the dominant factors influencing the economic viability of algae–based biochar systems. Across the literature, wastewater integration emerges as one of the most effective strategies for reducing operating expenses by decreasing the demand for synthetic nutrients and chemical additives. Furthermore, the economic performance of downstream conversion pathways has a direct influence on the production cost, which ultimately determines commercial competitiveness. However, despite widespread agreement on these trends, economic outcomes remain highly sensitive to assumptions regarding feedstock productivity, process scale, financing conditions, and market prices, limiting the comparability of results across studies (Figure 3).



Manuscript

Figure 3: Conceptual process flow diagram illustrating an integrated microalgae valorisation pathway, combining wastewater treatment and CO_2 utilization with the recovery of high-value compounds and biofuel production, followed by pyrolysis of residual algal biomass to produce algal biochar.

One of the most significant findings from large–scale assessments is the strong dependence of project economics on process configuration and capital intensity. Ranganathan et al. (2019) demonstrated that economically viable wastewater–based algae–to–fuel systems incorporating hydrothermal liquefaction and hydroprocessing require exceptionally high capital investments of approximately 492M €, with wastewater treatment and hydrothermal liquefaction units accounting for the majority of total capital expenditure. Although the study reported a competitive fuel price of approximately 0.99 € L^{-1}, this result raises important questions regarding scalability and investment risk. Achieving competitive fuel prices under highly capital–intensive configurations may be technically feasible, but it remains uncertain whether such projects can attract sufficient investment in the absence of strong policy support, carbon pricing mechanisms, or long–term fuel purchase agreements (Table 3).

Parameter	**Comparative characteristics / reported performance**	**References**
Adsorption capacity	Used for adsorption of Pb(II), other heavy metals, phosphorus and inorganic pollutants. Performance depends on pH, surface functional groups, pore structure, initial pollutant concentration and biochar modification. Reported capacities must be specified for each pollutant and adsorbent.	Binda et al. (2018); Kim et al. (2026); Show et al. (2024)
Heavy-metal immobilization	Potential for immobilization or removal of Pb, Cd, Cu and other metals through surface complexation, ion exchange, electrostatic attraction and precipitation.	Show et al. (2024); Kim et al. (2026)
Nutrient recovery	Algal biochar can retain mineral nutrients, including phosphorus, potassium, calcium and magnesium. Potential application as a nutrient-rich soil amendment.	Mustapha et al. (2025)

Accepted Manuscript

Agricultural performance	Potential improvement in soil nutrient retention, soil properties, water-holding capacity and plant growth. Crop responses depend on biochar dosage, soil characteristics and nutrient availability.	Mustapha et al. (2025)
Plant growth and crop yield	Potential use as a soil amendment and nutrient source. However, direct comparative crop-yield data for different algal biochars remain limited.	Mustapha et al. (2025)
Pollutant adsorption	Potential removal of inorganic pollutants from wastewater and contaminated water. Adsorption mechanisms include pore filling, electrostatic attraction, surface complexation, ion exchange and precipitation.	Kim et al. (2026)
Environmental application	Wastewater treatment, heavy-metal removal, nutrient recovery, soil amendment, carbon sequestration and environmental remediation.	Show et al. (2024); Mustapha et al. (2025)
Production cost	Influenced by algal cultivation, biomass harvesting, dewatering, drying, transportation, pyrolysis energy requirements and reactor design. No generally applicable commercial cost per kg or tonne has been established.	Mustapha et al. (2025)
Life-cycle assessment (LCA)	Important indicators include global warming potential (GWP), cumulative energy demand, water consumption, land use, acidification and eutrophication.	Mustapha et al. (2025); LCA review (2026)
Global warming potential (GWP)	A 2026 review reported a wide range of −1.54 to 1.36 × 10^3 kg CO_2-equivalent across assessed microalgal biochar pathways, reflecting differences in system boundaries and production assumptions.	LCA review (2026)
Environmental trade-offs	Drying and conversion energy requirements can increase environmental impacts. Wastewater-grown microalgae may reduce impacts associated with synthetic nutrient media.	LCA review (2026)

Accepted Manuscript

Commercial scalability	Potential for integration with wastewater treatment, CO_2 utilization and microalgal biorefineries. Major challenges include biomass harvesting, dewatering, energy consumption, product consistency and process economics.	Mustapha et al. (2025)

Table 3. Functional performance, environmental applications and economic sustainability.

Similarly, Karimi et al. (2025) found that the economics of biocrude production through hydrothermal liquefaction are overwhelmingly dominated by feedstock costs and conversion efficiency. The reported minimum fuel selling price of approximately 2.68 € L^{-1} was substantially higher than current fossil fuel prices, with feedstock costs accounting for approximately 87% of total production expenses. While improvements in biocrude yield from 51% to 60% reduced the minimum fuel selling price to 2.27 € L^{-1}, the system remained economically challenging. This finding highlights a broader issue within algae–based fuel systems: technological improvements alone may be insufficient to achieve competitiveness if biomass cultivation costs remain high. Consequently, many economic assessments may overestimate the benefits of conversion optimization while underestimating the structural challenges associated with feedstock production.

Wastewater–integrated cultivation systems generally improve cost competitiveness by reducing nutrient and chemical requirements. Mohit et al. (2024) demonstrated that greywater– based cultivation increased capital costs by 21% but reduced operating expenses by 40%, resulting in an approximately 50% reduction in biofuel selling price. This reflects a recurring pattern throughout the techno–economic literature, whereby integrated systems increase upfront investment requirements while generating long–term operational savings. Nevertheless, such economic advantages are highly dependent on stable wastewater availability and regulatory acceptance. The assumption that wastewater streams are consistently accessible and suitable for cultivation may not hold across different geographical and industrial contexts, potentially limiting the transferability of these results.

A similar trend was observed by Li et al. (2022), who reported that source–separated wastewater systems increased capital costs by 8.9% while reducing operating costs by 15.43%, resulting in only a modest increase in total system costs. More importantly, the minimum fuel selling price of bio–oil was substantially lower than that of conventional wastewater systems. These findings suggest that nutrient recovery architecture can significantly influence

Accepted Manuscript

commercial viability. However, they also reveal a potential weakness in many techno–economic studies: economic benefits are often attributed to idealized nutrient recovery efficiencies that may be difficult to achieve consistently at commercial scale. As a result, projected economic gains may be less robust under real–world operating conditions. The economics of carbon capture and sequestration systems integrated with algae differ substantially from those of fuel–focused biorefineries. Bhowmick et al. (2022) reported that economic performance is largely governed by module capital costs, harvesting intervals, and carbon sequestration efficiency. In these systems, profitability depends less on fuel production and more on the economic value assigned to carbon removal. Optimized harvesting intervals exceeding 6 to 10 months improved both environmental and economic outcomes. However, this dependence on carbon valuation introduces considerable uncertainty because future carbon credit markets remain volatile and heavily influenced by policy decisions. Consequently, favorable economic projections for carbon capture systems may be difficult to sustain if carbon prices decline or regulatory incentives change.

At a broader systems level, Zhang et al. (2026) demonstrated that deploying hybrid carbon capture and algae utilization systems across coal–fired power plants could reduce overall mitigation costs by approximately 4.25 G € under high–emission reduction scenarios. Importantly, the primary economic benefit originated not from fuel production itself but from reductions in carbon dioxide transport and storage costs combined with revenue generated from biomass products. This finding represents a shift away from conventional single–product techno–economic analyses toward integrated carbon economy frameworks. However, it also suggests that the economic rationale for algae systems increasingly depends on external system benefits rather than the intrinsic profitability of biofuel production. Such dependence may weaken the economic case where carbon management infrastructure is absent or poorly developed. Mohamed et al. (2023) further demonstrated that profitability varies substantially depending on feedstock selection. Sawdust–based co–pyrolysis systems achieved the highest net present value, whereas algae–based systems were less profitable due to lower bio–oil yields and inferior fuel quality. These results contrast with those reported for wastewater–integrated hydrothermal liquefaction systems, where integration strategies can partially offset cultivation costs. The comparison suggests that pyrolysis pathways are more sensitive to feedstock characteristics than hydrothermal liquefaction pathways. More broadly, it highlights a recurring challenge in the field: many techno–economic assessments focus on optimizing conversion technologies while overlooking the fundamental limitations imposed by phytomass quality and

Accepted Manuscript

availability. Ryland et al. (2026) demonstrated that nutrient removal credits are critical to the economic viability of algal turf scrubber systems. Without nutrient valuation, minimum fuel selling prices remained prohibitively high; however, after accounting for nutrient removal benefits, economically favorable conditions were achieved at up to 44 % of evaluated sites. This finding indicates that algal turf scrubber systems derive much of their value from wastewater treatment services rather than fuel production. Consequently, their commercial success may depend more on environmental credit schemes and regulatory incentives than on the market value of biofuels. This raises concerns regarding the long–term resilience of such systems if policy support changes.

Overall, techno–economic analyses reveal a persistent tension between productivity, capital intensity, and downstream processing costs. Hossain et al. (2026) illustrated this trade–off by comparing biodiesel and biohydrogen production pathways in Bangladesh. Biodiesel production required relatively low capital investment and achieved a shorter payback period, whereas biohydrogen production generated substantially higher revenues and net present value but required significantly greater investment, longer payback periods, higher greenhouse gas emissions, and less favorable energy performance. These findings demonstrate that economic optimization often conflicts with environmental objectives, making it difficult to identify universally superior pathways.

Similarly, Marousek et al. (2024) showed that cultivation technology strongly influences the economics of algae–derived biochar production in Central Europe. Open raceway ponds and open–air cultivation systems reduced production costs but increased variability in biomass quality, whereas photobioreactors provided greater process control at substantially higher production costs. Harvesting remained one of the largest economic burdens regardless of cultivation strategy, although switching from centrifugation to flocculation significantly reduced harvesting expenses. Collectively, these studies demonstrate that despite differences in end products, the same fundamental constraints continue to limit economic viability across algae–based systems: high cultivation costs, energy–intensive downstream processing, and expensive harvesting operations. Therefore, future improvements are unlikely to arise from isolated technological advances. Instead, meaningful economic progress will require integrated optimization of the entire biorefinery system, including cultivation, harvesting, conversion, resource recovery, and product valorization pathways. Furthermore, many published techno–economic analyses continue to rely on optimistic assumptions regarding biomass productivity,

Accepted Manuscript

conversion yields, and market conditions, suggesting that the commercial readiness of algae–based biorefineries may be less mature than reported economic projections imply.

4.1.Environmental Applications and Performance of Algae-Derived Biochar

Across the reviewed studies, algal biochar consistently demonstrated positive effects on soil physicochemical properties, nutrient cycling, microbial activity (Kabato et al., 2025), and plant stress tolerance. However, these benefits should be interpreted with caution. The agronomic performance of algal biochar is highly context–dependent, varying according to feedstock composition, pyrolysis conditions, soil characteristics, climatic conditions, and interactions with soil microbial communities. Moreover, many studies were conducted under controlled laboratory or greenhouse conditions, where environmental variability is minimized. Consequently, the reproducibility of these benefits under field–scale agricultural conditions remains uncertain.

A recurring observation throughout the literature is that algal biochar often performs most effectively when combined with complementary amendments such as microbial inoculants, nutrient–enriched formulations, digestates, or engineered surface modifications. While these integrated approaches frequently improve crop productivity and soil quality, they also increase system complexity and cost. This raises an important question regarding practical implementation: whether the observed agronomic benefits originate primarily from the biochar itself or from the additional biological and chemical inputs incorporated into the system. As a result, attributing improved crop performance solely to algal biochar may overstate its independent contribution.

The widespread use of nutrient enrichment and surface functionalization strategies further illustrates this limitation. Studies by Fertahi et al. (2024) and Zhou et al. (2024) demonstrated substantially greater plant growth responses from modified biochars than from untreated biochar. Although these findings highlight opportunities for performance optimization, they also suggest that raw algal biochar may not consistently provide sufficient agronomic value without additional processing. Such modifications increase production costs and may reduce the economic competitiveness of algal biochar compared with conventional soil amendments.

A further challenge concerns the economic feasibility of algal biochar production itself. Techno–economic assessments consistently identify algae cultivation, harvesting, dewatering, and thermochemical conversion as major cost drivers. Unlike typical lignocellulosic feedstocks such as forestry residues, digestate, crop wastes, or sludgechar, algal phytomass requires

Accepted Manuscript

resource–intensive cultivation and processing before biochar production can occur. Consequently, the production costs of algal biochar are substantially higher than those of many conventional biochars. This creates a fundamental mismatch between demonstrated agronomic benefits and economic viability. Although algal biochar may improve soil quality and crop performance, the magnitude of these benefits may not always justify the additional production costs, particularly in large–scale agricultural systems where low–cost amendments are generally preferred.

The variability in agronomic outcomes reported by Rawat et al. (2024) further emphasizes this challenge. While algae–derived products exhibited biostimulant properties, certain biochars produced under specific pyrolysis conditions inhibited seed germination. Such findings indicate that algal biochar cannot be assumed to provide universally positive outcomes. Instead, performance depends heavily on feedstock characteristics and process optimization, creating additional uncertainty for commercial deployment. Overall, the literature indicates that algal biochar has considerable potential as a multifunctional soil amendment capable of improving nutrient cycling, microbial activity, crop productivity, and environmental remediation. Nevertheless, significant limitations remain. The majority of reported benefits originate from short–term or controlled–environment studies, while evidence from long–term field trials remains limited. Furthermore, the high costs associated with algae cultivation and biochar production, together with the frequent requirement for nutrient enrichment or surface modification, raise concerns regarding economic scalability. Therefore, despite promising agronomic performance, the widespread adoption of algal biochar will likely depend on its integration within broader biorefinery systems where biochar functions as a value–added co–product rather than the primary economic output. Without such integration, algal biochar may struggle to compete economically with established biochar feedstocks and conventional soil amendments.

4.2.Soil amendment and agricultural productivity

Algae-derived biochar has potential as a soil amendment because of its mineral-rich composition, surface functional groups, and ability to influence soil physicochemical properties. Depending on the algal feedstock and conversion conditions, its application may modify soil pH, electrical conductivity, nutrient availability, water retention, and microbial activity. These properties are particularly relevant for soils affected by nutrient depletion, salinity, and other forms of degradation.

Accepted Manuscript

The agricultural performance of algae-derived biochar is not determined exclusively by its carbon content. Its mineral composition, including retained nitrogen, phosphorus, potassium, calcium, and magnesium, may contribute to nutrient cycling and soil fertility. Furthermore, biochar surfaces can provide sites for nutrient retention and microbial colonization, potentially influencing soil biological processes.

Kabato et al. (2025) discussed the potential of microalgae-based strategies to improve soil health and crop productivity. Fertahi et al. (2024) demonstrated improved tomato growth using agricultural inputs based on biochar impregnated with algal residue extracts. These findings indicate the potential of combining algal-derived materials with biochar to enhance agricultural performance. However, the contribution of the biochar itself should be distinguished from the additional effects of incorporated extracts or other amendments.

Despite promising results, the agronomic effectiveness of algae-derived biochar remains dependent on soil type, application rate, feedstock composition, pyrolysis temperature, and crop characteristics. Consequently, long-term field trials are required to establish appropriate application rates, evaluate repeated applications, and determine whether improvements observed under controlled conditions can be maintained under agricultural field conditions.

4.3.Heavy-metal immobilization and contaminated soil remediation

The immobilization of potentially toxic metals represents an important environmental application of algae-derived biochar. Heavy metals such as Pb, Zn, Cd, and Cu can persist in contaminated soils and negatively affect soil microorganisms, plant development, and environmental quality. Biochar may reduce their mobility through surface complexation, ion exchange, electrostatic interactions, and precipitation reactions. Myung et al. (2024) investigated Spirulina platensis-derived biochar for the adsorption of Pb and Zn and improvement of soil physicochemical properties. Their findings support the potential use of algal biochar in contaminated soil management. The effectiveness of immobilization is influenced by biochar surface chemistry, mineral composition, pH, contaminant concentration, and soil characteristics.

However, a reduction in the mobility of heavy metals should not be interpreted as their complete removal from contaminated soil. Immobilized metals may remain in the soil matrix and could potentially become mobile again under changing environmental conditions. Therefore, long-term monitoring of metal speciation, leaching behavior, and plant uptake is necessary to evaluate the stability of remediation outcomes.

Accepted Manuscript

4.4.Adsorption of organic and inorganic pollutants

Algae-derived biochar also offers opportunities for removing organic and inorganic contaminants from aqueous environments. Its adsorption performance depends on pore structure, specific surface area, surface functional groups, solution pH, initial contaminant concentration, and biochar modification.

For inorganic pollutants, adsorption may occur through electrostatic attraction, ion exchange, surface complexation, and precipitation. For organic contaminants, possible mechanisms include pore filling, hydrophobic interactions, hydrogen bonding, and interactions with aromatic carbon structures. Chemical activation and surface functionalization may improve adsorption performance by increasing accessible surface area and introducing additional binding sites.

Bhowmick et al. (2022) investigated specially designed algae-lignocellulosic biochar for the adsorption of metformin, demonstrating the potential of engineered biochar mixtures for pharmaceutical contaminant removal. Similarly, Myung et al. (2024) demonstrated the adsorption potential of Spirulina-derived biochar for Pb and Zn. Aljaziri et al. (2026) further highlighted the potential of nitrogen-enriched algal biochar for water purification and resource recovery.

Nevertheless, adsorption performance reported under laboratory conditions does not automatically establish suitability for real wastewater treatment. Competitive adsorption, dissolved organic matter, ionic strength, biochar regeneration, and the disposal of contaminantloaded adsorbents must also be considered. Further research should therefore evaluate adsorption capacity under realistic wastewater conditions and establish the environmental safety of regenerated biochar and spent adsorbents.

4.5.Nutrient recovery and wastewater treatment

Algae-derived biochar may contribute to nutrient recovery and wastewater treatment through the retention of phosphorus and other mineral nutrients. Algal biomass naturally incorporates nutrients during cultivation, and a proportion of these nutrients may remain in the solid fraction following thermochemical conversion. The resulting mineral-rich biochar may therefore offer opportunities for recovering resources from wastewater-derived biomass. The performance of nutrient-rich biochar depends on the original biomass composition and conversion conditions. In particular, phosphorus retention, mineral phase formation, and nutrient availability may

Accepted Manuscript

influence its suitability as a soil amendment or nutrient-recovery material. Surface modification and mineral enrichment may further improve nutrient capture and retention.

The integration of wastewater-based algal cultivation with subsequent biochar production provides a potential pathway for linking wastewater treatment, biomass valorization, and nutrient recycling. However, the effectiveness of such systems depends on the wastewater composition, nutrient removal efficiency, biomass productivity, and contaminant accumulation during cultivation.

Further studies should quantify nutrient mass balances across the cultivation medium, harvested biomass, biochar, and liquid conversion products. Such information is necessary to determine whether nutrient recovery through algae-derived biochar offers a measurable environmental advantage over conventional nutrient-recovery approaches.

5.5. Environmental risks and long-term stability

Despite its potential environmental benefits, algae-derived biochar may present risks associated with contaminant accumulation, nutrient release, and changes in soil physicochemical conditions. These concerns are particularly relevant when biomass originates from municipal or industrial wastewater. Heavy metals and persistent organic contaminants accumulated during cultivation may become concentrated or redistributed during thermochemical conversion.

Another important consideration is the long-term stability of algae-derived biochar. Although thermochemical conversion promotes carbonization and the formation of relatively stable carbon structures, carbon persistence depends on feedstock composition, conversion temperature, residence time, and environmental conditions following application. Consequently, the presence of carbon in biochar should not automatically be interpreted as permanent carbon sequestration. Biochar application may also influence soil pH, electrical conductivity, nutrient availability, and microbial activity. Although these changes can be beneficial under appropriate conditions, excessive application or unsuitable biochar characteristics may adversely affect seed germination and plant development. Rawat et al. (2024), for example, reported that certain biochars produced under specific pyrolysis conditions inhibited seed germination, illustrating the importance of evaluating biochar quality before agricultural application.

Accordingly, future studies should prioritize standardized contaminant testing, leaching assessments, ecotoxicological evaluation, long-term soil experiments, and carbon stability

Accepted Manuscript

measurements. Such investigations are necessary to establish safe application conditions and ensure that the environmental benefits of algae-derived biochar are maintained over extended periods.

5. Conclusion and future research directions

Although algae-derived biochar is frequently presented in the literature as a promising component of circular bioeconomy systems, the prevailing optimism often overlooks the technical, techno-economic, and regulatory realities governing its commercial deployment. Much of the available evidence originates from laboratory-scale experiments or modelling studies relying on favorable assumptions regarding wastewater integration, carbon credits, and environmental incentives. Under real-world conditions, cultivation, harvesting, dewatering, and thermochemical conversion remain substantial cost and energy bottlenecks. Consequently, algae-derived biochar is unlikely to compete economically with conventional waste-derived biochars solely on the basis of its production cost or carbon sequestration potential.

Overcoming these limitations requires, above all, substantial advances in algal biomass harvesting and dewatering, alongside reductions in the energy demand of biomass processing and thermochemical conversion. Nevertheless, even significant improvements in production efficiency may not be sufficient to establish the competitive advantage required for market penetration. A more promising strategy may lie in transforming algaederived biochar from a relatively expensive carbonaceous material into a high-performance sorbent and carrier for agricultural chemicals and soil amendments. In particular, functionalization using bio-based natural deep eutectic solvents (NaDES) could enable the development of advanced, controlled-release agrochemical formulations combining nutrient delivery, improved sorption properties, and the benefits of stable carbon incorporation into soils.

Such multifunctional products could create substantially greater added value than conventional biochar applications while potentially reducing the carbon footprint of agricultural inputs. Future research should therefore move beyond demonstrating the technical feasibility of algal biochar production towards integrated pilot-scale validation, comprehensive mass and energy balances, regulatory compliance, long-term agronomic

Accepted Manuscript

performance, and robust techno-economic and life-cycle assessments. Ultimately, the commercial potential of algae-derived biochar will depend less on its ability to be produced than on its ability to deliver a demonstrable functional and economic advantage over cheaper competing materials.

6. References

1. Afshar, Maryam, and Saeed Mofatteh. 2024. "Biochar for a Sustainable Future: Environmentally Friendly Production and Diverse Applications." *Results in Engineering* 23(June): 102433. doi:10.1016/j.rineng.2024.102433.
2. Ali, Aamir, Nida Jabeen, Zaid Chachar, Sadaruddin Chachar, Shoaib Ahmed, Nazir Ahmed, Azhar Laghari, et al. 2025. "The Role of Biochar in Enhancing Soil Health & Interactions with Rhizosphere Properties and Enzyme Activities in Organic Fertilizer Substitution." *Frontiers in Plant Science* 16. doi:10.3389/fpls.2025.1595208.
3. Aljaziri, Jinan, Ribhu Gautam, Kyle J Lauersen, and S Mani Sarathy. 2026. "Microwave Assisted Pyrolysis of Nitrogen–Rich Biomass: Sustainable Biochar for Water Purification and Resource Recovery." *Biomass and Bioenergy* 208: 108899. doi:https://doi.org/10.1016/j.biombioe.2025.108899.
4. Anto, Susaimanickam, M P Sudhakar, Tharifkhan Shan Ahamed, Melvin S Samuel, Thangavel Mathimani, Kathirvel Brindhadevi, and Arivalagan Pugazhendhi. 2021. "Activation Strategies for Biochar to Use as an Efficient Catalyst in Various Applications." *Fuel* 285: 119205. doi:https://doi.org/10.1016/j.fuel.2020.119205.
5. Anwar, Muhammad, Muhammad Farooq Qayyum, Hafiz Muhammad Zubair, and Muhammad Aon. 2026. "Soil Applied Biochars and Foliar Applied Nanoparticles Improve Wheat Growth in Cadmium Contaminated Soil." *Plant Nano Biology* 15: 100241. doi:https://doi.org/10.1016/j.plana.2025.100241.
6. Arias–Lizárraga, Dulce María, Martín Barragán–Trinidad, Angélica Guillén–Garcés, Lourdes Fonseca–Campos, Diego González–Altamirano, and Patrick U Okoye. 2025. "A Circular Economy Approach for Sustainable Biohydrogen, Activated Carbon and Biofertilizers in a Microalgae–Based Wastewater Treatment." *International Journal of Hydrogen Energy* 148: 150046. doi:https://doi.org/10.1016/j.ijhydene.2025.150046.
7. De Bhowmick, Goldy, Rowena M. Briones, Sören Thiele–Bruhn, Ramkrishna Sen, and

Accepted Manuscript

Ajit K. Sarmah. 2022. “Adsorptive Removal of Metformin on Specially Designed Algae–Lignocellulosic Biochar Mix and Techno–Economic Feasibility Assessment.” *Environmental Pollution* 292(September 2021). doi:10.1016/j.envpol.2021.118256.

8. Braud, Léa, Vitor Verdelho, Silvio Mangini, Monique Ras, Jean–Paul Cadoret, and Carlos Unamunzaga. 2025. “Life Cycle Assessment of Algal Products: A Step–by–Step Guide to Application.” : 23. https://lca.eaba–association.org/resources.
9. Campion, Luca, Madina Bekchanova, Robert Malina, and Tom Kuppens. 2023. “The Costs and Benefits of Biochar Production and Use: A Systematic Review.” *Journal of Cleaner Production* 408: 137138. doi:10.1016/J.JCLEPRO.2023.137138.
10. Cole, Garrett M., Jonah M. Greene, Jason C. Quinn, Beth McDaniel, Lisa Kemp, David Simmons, Tyler Hodges, et al. 2023. “Integrated Techno–Economic and Life Cycle Assessment of a Novel Algae–Based Coating for Direct Air Carbon Capture and Sequestration.” *Journal of CO2 Utilization* 69(February): 102421. doi:10.1016/j.jcou.2023.102421.
11. Elango, Agila, Mauli Goel, Gopalakrishnan Kumar, Chandramughi V P, Vishnu Priya V, Chawalit Ngamcharussrivichai, Flora G, and Veeramuthu Ashokkumar. 2026. “Biochar Production with Concomitant Biopolymer Accumulation of Microalgae–Based Wastewater Treatment for Carbon Neutrality.” *DeCarbon* 12: 100162. doi:https://doi.org/10.1016/j.decarb.2026.100162.
12. Falchetto, L. H. S., et al. (2026). Structural characterization and biochar potential of Spirulina sp. LEB 18. Biomass and Bioenergy. https://doi.org/10.1016/j.biombioe.2026.109808
13. Fertahi, Saloua, Doha Elalami, Saida Tayibi, Adnane Bargaz, and Abdellatif Barakat. 2024. “Multifunctional Agricultural Inputs Based on Biochar Impregnated with Algae Residues Extracts: Promoting Effect on Tomato Growth.” *Algal Research* 81: 103577. doi:https://doi.org/10.1016/j.algal.2024.103577.
14. Fu, Yu, Qingran Zhang, Zhengying Tan, Songxia Yu, and Yi Zhang. 2025. “Predicting Harvesting Efficiency of Microalgae with Magnetic Nanoparticles Using Machine Learning Models.” *Journal of Environmental Chemical Engineering* 13(2). doi:10.1016/j.jece.2025.115406.
15. Gawali, Sushant, Shahrukh Nawaj Alam, Jeel Tilva, Krushna Jagadale, Bhaskar Singh, and Abhishek Guldhe. 2025. “Development of Scalable Cultivation Strategy for Microalgal Biomass Generation Using Wastewater and Integrated Biorefinery

Accepted Manuscript

Approach for Biofuel Production." *Journal of Environmental Chemical Engineering* 13(2): 115441. doi:https://doi.org/10.1016/j.jece.2025.115441.

16. Hait, Sinchan, Sushant Gawali, Pranay Awathare, Shahrukh Nawaj Alam, Bhaskar Singh, and Abhishek Guldhe. 2024. "Integrated Approach for Microalgal Biomass Generation Using Poultry Litter and Wastewater–Based Media and Its Application for Bio–Oil Production." *Energy Conversion and Management* 313(May): 118610. doi:10.1016/j.enconman.2024.118610.
17. Hossain, Md Sanowar, Md Shazu Ahamed Anik, Fardin Al Rafin, Shahinul Alam, Abdullah Adnan Abir, Monjur Mourshed, and Md Rasel Ahmed. 2026. "Microalgae for Sustainable Energy: Techno–Economic and Life Cycle Insights into Biodiesel and Biohydrogen Production." *Energy Conversion and Management: X* 30(January): 101840. doi:10.1016/j.ecmx.2026.101840.
18. Ighalo, Joshua O, Kanika Dulta, Setyo Budi Kurniawan, Fredrick O Omoarukhe, Ugochukwu Ewuzie, Steve O Eshiemogie, Alaba U Ojo, and Siti Rozaimah Sheikh Abdullah. 2022. "Progress in Microalgae Application for CO2 Sequestration." *Cleaner Chemical Engineering* 3: 100044. doi:https://doi.org/10.1016/j.clce.2022.100044.
19. Junejo, Abdul Rahim, Jinrui Liu, Keyue Chen, Shahzad Hussain Dahri, Yasmin Junejo, and Hao Li. 2026. "Biochar for Sustainable and Climate–Resilient Agriculture: The 3Ps Approach." *Biomass and Bioenergy* 210: 109001. doi:https://doi.org/10.1016/j.biombioe.2026.109001.
20. Kabato, Wogene Solomon, Niguss Hailegnaw, Tesfatsion Ermias Chaffamo, Asish Samuel, Agampodi Gihan S.D. De Silva, and Zoltán Molnár. 2025. "Microalgae–Based Strategies for Soil Health and Crop Productivity: Mechanisms, Challenges, and Pathways to Climate–Resilient Agriculture." *Agronomy* 15(11): 1–32. doi:10.3390/agronomy15112669.
21. Kamngoen, Apiwit, Antira Wichaphian, Ratanaporn Kanyamee, Wasu Pathom–aree, Wassana Kamopas, Wageeporn Maneechote, Yupa Chromkaew, et al. 2026. "Microalgal Chlorella Biomass and Biorefinery Residue–Derived Biochar Combined with Actinobacteria: A Biofertilizer Strategy to Enhance Lettuce Growth and Rhizosphere Microbial Dynamics." *Algal Research* 95: 104679. doi:https://doi.org/10.1016/j.algal.2026.104679.
22. Karimi, Mahmoud, and Halis Simsek. 2025. "Life Cycle Assessment and Techno–Economic Optimization of Biocrude Oil Production from Microalgae via Hydrothermal

Accepted Manuscript

Liquefaction Using Genetic Algorithms." *Journal of Cleaner Production* 520(April): 146104. doi:10.1016/j.jclepro.2025.146104.

23. Khoo, Kuan Shiong, Imran Ahmad, Kit Wayne Chew, Koji Iwamoto, Amit Bhatnagar, and Pau Loke Show. 2023. "Enhanced Microalgal Lipid Production for Biofuel Using Different Strategies Including Genetic Modification of Microalgae: A Review." *Progress in Energy and Combustion Science* 96(February): 101071. doi:10.1016/j.pecs.2023.101071.
24. Kim, M. J., et al. (2026). Algal biochar for inorganic pollutant removal via adsorption process: synthesis, solution chemistry, and mechanistic insights. Journal of Water Process Engineering, 83, 109708. Read article.
25. Li, Peiyao, Yiqing Luo, and Xigang Yuan. 2022. "Life Cycle and Techno–Economic Assessment of Source–Separated Wastewater–Integrated Microalgae Biofuel Production Plant: A Nutrient Organization Approach." *Bioresource Technology* 344(PB): 126230. doi:10.1016/j.biortech.2021.126230.
26. Ma, Chao, Zhe Xu, Wei Yang, Tao Tang, Qi Liu, Dongliang Zhang, Prashanth Prasanna, and Zhongyi Qu. 2025. "Co–Application of Microalgae and Biochar Increases Yield and Mitigates Greenhouse Gas Emissions in Saline–Alkali Soil." *Field Crops Research* 327: 109885. doi:https://doi.org/10.1016/j.fcr.2025.109885.
27. Mardoyan, A., & Braun, P. (2015). Analysis of Czech subsidies for solid biofuels. *International Journal of Green Energy*, *12*(4), 405–408.
28. Marousek, Josef, Beata Gavurova, and Anna Marouskova. 2024. "Cost Breakdown Indicates That Biochar Production from Microalgae in Central Europe Requires Innovative Cultivation Procedures." *Energy Nexus* 16: 100335. doi:10.1016/j.nexus.2024.100335.
29. Minofar, Babak, Nevena Milčić, Josef Maroušek, Beata Gavurová, and Anna Marouškova. 2025. "Understanding the Molecular Mechanisms of Interactions between Biochar and Denitrifiers in N_2O Emissions Reduction: Pathway to More Economical and Sustainable Fertilizers." *Soil and Tillage Research* 248. doi:10.1016/j.still.2024.106405.
30. Marousek, J., Gavurova, B., Marouškova, A., & Minofar, B. (2026). Exfoliated biochar activates soil microbial metabolism and demonstrates immobilization potential toward toxic metals and metalloids. *Systems Microbiology and Biomanufacturing*, *6*(3), 89.

Accepted Manuscript

31. Mohamed, Badr A., Marnie O'Boyle, and Loretta Y. Li. 2023. "Co–Pyrolysis of Sewage Sludge with Lignocellulosic and Algal Biomass for Sustainable Liquid and Gaseous Fuel Production: A Life Cycle Assessment and Techno–Economic Analysis." *Applied Energy* 346(June): 121318. doi:10.1016/j.apenergy.2023.121318.
32. Mohit, Aggarwal, V. Kuttickal Mishel, and Neelancherry Remya. 2024. "Life Cycle Assessment and Technoeconomic Analysis of Biofuels Produced from Polyculture Microalgae Cultivated in Greywater." *Journal of Environmental Management* 356(November 2023): 120711. doi:10.1016/j.jenvman.2024.120711.
33. Mustapha, S. I., & Isa, Y. M. (2025). Thermal Conversion of Microalgae into Biochar: A Review on Processes, Properties, and Applications. ChemBioEng Reviews, 12(1). https://doi.org/10.1002/cben.202400035
34. Myung, Eunji, Hyunsoo Kim, Nagchoul Choi, and Kanghee Cho. 2024. "The Biochar Derived from Spirulina Platensis for the Adsorption of Pb and Zn and Enhancing the Soil Physicochemical Properties." *Chemosphere* 364: 143203. doi:https://doi.org/10.1016/j.chemosphere.2024.143203.
35. Nawaz, A., et al. (2024). Engineered biochar-based catalytic pyrolysis of Spirulina platensis microalgae for the production of high value compounds in microwave reactor. Algal Research, 81, 103583. Read article
36. Omokaro, Godspower Oke, Konstantin Pavlovich Kornev, Zipporah Simiyu Nafula, Abdulmajeed Allan Chikukula, Osazemen Godswill Osayogie, and Ogheneochuko Shadrack Efeni. 2025. "Biochar for Sustainable Soil Management: Enhancing Soil Fertility, Plant Growth and Climate Resilience." *Farming System* 3(4): 100167. doi:https://doi.org/10.1016/j.farsys.2025.100167.
37. Parthipan, Punniyakotti, Murali Santhoshkumar, D. Shanmugapriya, Prathapavarma Digala, Mohammed Mujahid Alam, Abdullah G. Al–Sehemi, and Kuppusamy Sathishkumar. 2026. "Toward Zero–Waste Seaweed Biorefineries: Life Cycle–Guided Green Extraction and Process Intensification Strategies." *Algal Research* 97: 104778. doi:10.1016/J.ALGAL.2026.104778.
38. Ranganathan, Panneerselvam, and Sivaraman Savithri. 2019. "Techno–Economic Analysis of Microalgae–Based Liquid Fuels Production from Wastewater via Hydrothermal Liquefaction and Hydroprocessing." *Bioresource Technology* 284(January): 256–65. doi:10.1016/j.biortech.2019.03.087.
39. Rawat, Jyoti, Manisha Nanda, Sanjay Kumar, Nishesh Sharma, Rohit Sharma, Harish

Accepted Manuscript

Chandra Joshi, Mikhail S Vlaskin, Afzal Hussain, and Vinod Kumar. 2024. “Integrating Wastewater Treatment to Bio–Stimulant & Biochar Generation for Plant Growth Promotion Using Microalgae.” *Process Biochemistry* 145: 187–94. doi:https://doi.org/10.1016/j.procbio.2024.06.031.

40. Roy, Hari Prosad, Khalifa S.H. Eldiehy, and Dhanapati Deka. 2025. “Phycoremediation of Wastewater and Valorization of Chlorella Homosphaera Biomass for Biodiesel, Bio–Oil and Biochar Production via in–Situ Transesterification and Pyrolysis in a Biorefinery Framework.” *Biomass and Bioenergy* 203: 108270. doi:10.1016/J.BIOMBIOE.2025.108270.
41. Ryland, Ashley, Peter H. Chen, Mark Zivojnovich, Sungwhan Kim, Ryan W. Davis, Tyler Eckles, Jason C. Quinn, and David Quiroz. 2026. “Techno–Economic Analysis and Life Cycle Assessment of Algal Turf Scrubbers Treating Wastewater Effluent for Renewable Diesel Production.” *Algal Research* 93(December 2025): 104459. doi:10.1016/j.algal.2025.104459.
42. Segers, Britt, Philippe Nimmegeers, Marc Spiller, Giorgio Tofani, Edita Jasiukaitytė–Grojzdek, Elina Dace, Timo Kikas, et al. 2024. “Lignocellulosic Biomass Valorisation: A Review of Feedstocks, Processes and Potential Value Chains and Their Implications for the Decision–Making Process.” *RSC Sustainability* 2(12): 3730–49. doi:10.1039/d4su00342j.
43. Sharma, Tarun, Arkaprava Roy, Priyanka Saha, Alekhya Gunturi, Sunil Kumar Prajapati, Nilutpal Saikia, Lalit Kumar Mainway, and Alok Sinha. 2026. “Agronomical and Technological Advances for Carbon–Negative Agriculture and Carbon Credit BT – Carbon–Negative Agriculture.” In eds. Ram Swaroop Meena, Sandeep Kumar, Gourisankar Pradhan, Manoj Kumar Jhariya, and Cherukumalli Srinivasarao. Singapore: Springer Nature Singapore, 97–146. doi:10.1007/978–981–95–1483–0_4.
44. Show et al. (2024). Research advances on production and application of algal biochar in environmental remediation. Environmental Pollution. https://doi.org/10.1016/j.envpol.2024.123860
45. Singh, Asha, Rozi Sharma, Deepak Pant, and Piyush Malaviya. 2021. “Engineered Algal Biochar for Contaminant Remediation and Electrochemical Applications.” *Science of the Total Environment* 774: 145676. doi:10.1016/j.scitotenv.2021.145676.
46. Song, Qingqing, Fanying Kong, Bing–Feng Liu, Xueting Song, Xin Tan, Nan–Qi Ren, and Hong–Yu Ren. 2026. “Synergistic Coupling of Microalgae and Corn Cob Residue

Accepted Manuscript

Biochar for Enhanced Lipid Production and Heavy Metal Removal from Waste Leachate and Corn Cob Hydrolysate." *Energy* 347: 140430. doi:https://doi.org/10.1016/j.energy.2026.140430.

47. Strunecký, O., Shreedhar, S., Kolář, L., & Maroušková, A. (2025). Changes in soil water retention following biochar amendment. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *47*(1), 7145–7152.
48. Sun, Jiacheng, Verónica Benavente, and Ondřej Mašek. 2024. "Synergistic Valorisation of Wastewater Microalgae: Sulphuric Acid–Assisted Phosphorus Recovery and Enhanced Electrochemical Performance of Biochar for Supercapacitors." *Chemical Engineering Journal* 494(May). doi:10.1016/j.cej.2024.152986.
49. Tan, Xuefei, Fengfa Zhang, Huiwen Wang, and Shih Hsin Ho. 2023. "The Magic of Algae–Based Biochar: Advantages, Preparation, and Applications." *Bioengineered* 14(1): 2252157. doi:10.1080/21655979.2023.2252157.
50. Thanaraj, Thiviya AP, Shafirah Samsuri, Usman Bello, and Chai Yee Ho. 2025. "Optimization of Bio–Oil and Biochar Production from Defatted Microalgae Biomass via Microwave–Assisted Catalytic Cracking." *Journal of the Indian Chemical Society* 102(9): 101944. doi:10.1016/j.jics.2025.101944.
51. Vochozka, M., Maroušková, A., Váchal, J., & Straková, J. (2016). The economic impact of biochar use in Central Europe. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *38*(16), 2390–2396.
52. Wang, Zhicong, Yulu Yang, Jingjie Gao, Changqing Cao, and Peigao Duan. 2026. "Recent Progress in the Life Cycle Assessment and Technoeconomic Analysis of Microalgae Culture and the Preparation of Sustainable Aviation Fuel." *Biomass and Bioenergy* 206(November 2025): 108682. doi:10.1016/j.biombioe.2025.108682.
53. Wen, Hao, Haowen Zhang, Mengya He, and Xin Zhang. 2021. "A Novel Approach for Harvesting of the Microalgae Chlorella Vulgaris with Moringa Oleifera Extracts Microspheres by Buoy–Bead Flotation Method." *Algal Research* 60(March): 102479. doi:10.1016/j.algal.2021.102479.
54. Xu, Huanan, Hao Zhou, Yinfeng Hua, Weihua Chen, Jian Wu, Zhenwu Long, Liang Zhao, et al. 2025. "MgFe–LDH Engineered Biochar Self–Assembled with Chlorella Pyrenoidosa for Enhanced CO2 Capture and Microalgal Cultivation." *Chemical Engineering Journal* 525: 170075. doi:https://doi.org/10.1016/j.cej.2025.170075.

Accepted Manuscript

55. Yu, K. L., et al. (2017). Recent developments on algal biochar production and characterization. Bioresource Technology, 246, 2–11. Read article.
56. Zhang, Zezhou, Yupeng Sang, Kai Tong, Yaoqi Hou, Shuai Liu, Yutaka Kitamura, and Chunfeng Song. 2026. "Co–Deploying Algal Biocarbon Capture with Coal Power in China Reduces Carbon Emissions and Improves Cost–Effectiveness." *Sustainable Production and Consumption* 63(December 2025): 153–66. doi:10.1016/j.spc.2026.01.007.
57. Zhou, Yige, Zehui Liu, Jinhua Shan, Chengyang Wu, Eric Lichtfouse, and Hongbo Liu. 2024. "Efficient Recovery of Phosphate from Urine Using Magnesite Modified Corn Straw Biochar and Its Potential Application as Fertilizer." *Journal of Environmental Chemical Engineering* 12(2): 111925. doi:https://doi.org/10.1016/j.jece.2024.111925.

Acknowledgement

This paper was supported by the Slovak Research and Development Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic within projects APVV–24–0596 and APVV–24–0607.

Accepted Manuscript