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# Beyond Biomass: Reimagining Microalgae as Living Environmental Nano-Factories

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## Abstract

Microalgae have long been recognized for their potential in biofuel production and wastewater treatment, but their broader capabilities remain underexplored. This opinion paper presents a case for a significant shift in how microalgae are conceptualized from biomass producers to dynamic, multifunctional systems that can serve as environmental nano-factories. It highlights emerging research on the role of microalgae in heavy metal sequestration, the green biosynthesis of metal nanoparticles, and the cascading valorization of residual biomass through environmentally sustainable extraction methods. Together, these applications offer a unified platform for pollution mitigation and the production of valuable materials. The paper also examines recent progress in synthetic biology, bioreactor design, and microbial consortia that could support this transition. At the same time, it acknowledges key challenges, including issues of scalability, regulatory acceptance, and process integration. Strategic recommendations are proposed to advance this field and align it more closely with circular economy models. By reimagining microalgae as living nano-factories, this paper outlines a path forward for developing integrated, sustainable technologies that simultaneously address environmental and industrial challenges.

**Keywords:** microalgae; bioremediation; green nanoparticle synthesis; synthetic biology; circular economy

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## 1. Introduction

Microalgae, long recognized as the photosynthetic engines of aquatic ecosystems, have drawn sustained scientific interest due to their exceptional productivity, metabolic adaptability, and ecological importance. These diverse microorganisms contribute substantially to global primary production, form the basis of aquatic food webs, and play critical roles in carbon and nutrient cycling. Their biotechnological potential has been widely explored over recent decades, with applications ranging from biofuel production and wastewater treatment to carbon sequestration and the generation of high-value compounds such as pigments, polyunsaturated fatty acids, antioxidants, and nutraceuticals [1–4].

Despite significant progress in algal biotechnology and growing industrial engagement, microalgae are often still conceptualized narrowly as biomass producers. Whether utilized for third-generation biofuel feedstocks or as protein sources for aquaculture, their value is frequently framed in terms of biomass yield alone. This limited perception persists even as global sustainability challenges necessitate more integrated, multifunctional solutions. It is increasingly clear that microalgae should be re-envisioned, not merely as biomass-generating organisms but as dynamic biological platforms capable of orchestrating

complex environmental and chemical transformations. Beyond traditional remediation and resource recovery, microalgae can biosynthesize functional nanomaterials, facilitate green chemistry applications, and underpin circular economy frameworks [5]. Expanding the role of microalgae in this manner calls for a shift in both research focus and industrial innovation models, with an emphasis on multifunctionality, systems integration, and life-cycle sustainability. Transitioning from viewing microalgae solely as bioproduct generators to recognizing them as living nano-factories offers a robust framework to address environmental pollution, enable green manufacturing, and advance regenerative economic models. This paper discusses emerging frontiers in microalgal research and outlines pathways for positioning microalgae at the forefront of sustainable technological innovation (Figure 1). However, it must be noted that these roles for microalgae have so far been demonstrated only in isolation. A fully integrated system combining bioremediation, nanoparticle synthesis, and cascading biomass valorization remains conceptual and unproven to date; therefore, this vision is presented as an aspirational framework that requires further validation.

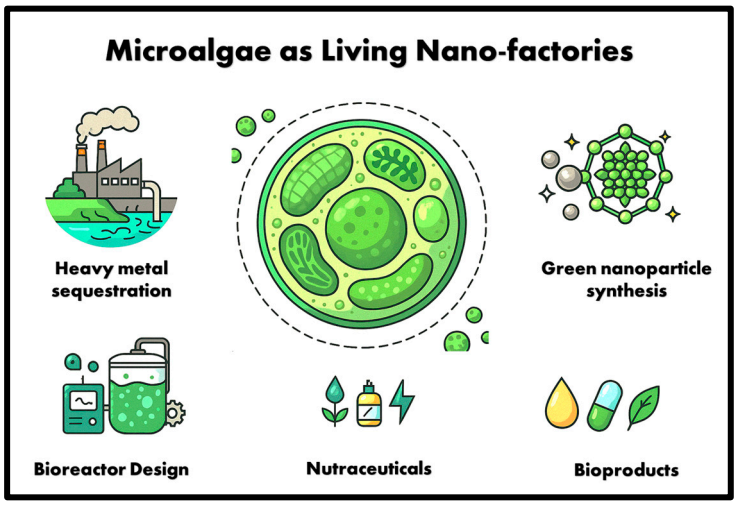



**Figure 1.** Microalgae as living nano-factories.

## 2. Beyond Conventional Bioremediation: Heavy Metal Sequestration and Beyond

Microalgae's capabilities in bioremediation, particularly heavy metal removal from contaminated waters, are well documented but remain underexploited at scale. Various freshwater and marine microalgal species demonstrate the capacity to adsorb, bioaccumulate, and detoxify heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), nickel (Ni), and zinc (Zn) [5–7]. These processes encompass multiple mechanisms, including passive adsorption via functional groups on cell surfaces, active intracellular uptake through metal ion transporters, and enzymatic detoxification, which results in the precipitation of metals as inert granules [8]. These biological mechanisms often achieve metal removal efficiencies comparable to or exceeding those of conventional chemical treatments under environmentally benign conditions. Laboratory studies have consistently demonstrated the ability of species such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Dunaliella salina* to achieve metal removal rates exceeding 80–90% under optimal conditions [9]. Extremophilic species, such as Galdieria sulphuraria, offer additional advantages, thriving at temperatures above 40 °C and pH values below 3, conditions characteristic of industrial effluents, including acid mine drainage (AMD) [8,10,11]. The extreme environmental tolerance of *G. sulphuraria* makes it a compelling candidate for application in harsh industrial waste streams, with demonstrated capabilities for removing cadmium, lead, nickel, and zinc, even in mixed-metal systems [8]. Field-scale validation is underway, such

as coal mine effluent treatment systems in South Africa, where selected microalgal consortia have achieved zinc and cadmium removal efficiencies exceeding 90% and have successfully removed aluminum and copper with 100% efficiency, outperforming conventional lime precipitation techniques while simultaneously generating valuable biomass [12].

Nevertheless, full industrial deployment faces persistent challenges, including the difficulty of maintaining stable cultures under non-sterile conditions, achieving cost-effective biomass harvesting and integrating algal systems within existing infrastructures. Importantly, microalgal heavy metal remediation should not be viewed solely as a strategy for pollutant removal. The resulting metal-enriched biomass represents an opportunity for resource recovery through metal desorption or transformation into functional nanomaterials. This approach aligns with circular economy principles by transforming waste streams into value streams and moving beyond the traditional "take–make–dispose" paradigm. Conceptualizing microalgal remediation as an active resource recovery strategy opens new dimensions for environmental and economic impact. While many microalgal strains used industrially are thermophilic, limiting their application to warmer regions, several cold-adapted species, such as *Chlamydomonas nivalis* and certain *Chlorella* strains, are available for use in colder climates. The implementation of microalgae-based technologies can therefore be geographically diversified, extending beyond traditionally warmer regions into temperate and even polar areas. Selection of species suited to local environmental conditions, including temperature and seasonal variations, is essential for sustainable large-scale deployment [13].

## 3. Biosynthesis of Metal Nanoparticles: Toward Green Nanotechnology

Beyond pollutant removal, microalgae offer the unique capability to biosynthesize functional nanoparticles (NPs) from sequestered metals, presenting new opportunities for green nanotechnology. Traditional NP synthesis methods often rely on high-temperature processes and toxic chemical reagents, generating hazardous byproducts and requiring significant energy inputs [14]. In contrast, microalgae facilitate nanoparticle formation under ambient conditions in aqueous systems, avoiding the need for toxic chemicals and offering a sustainable alternative. Microalgal nanoparticle biosynthesis can occur via intracellular or extracellular pathways. Intracellularly, metal ions are transported into the cells and reduced by biomolecules such as reductases, glutathione, or NAD(P)H-dependent systems, leading to nanoparticle formation within organelles like chloroplasts or mitochondria. Extracellular synthesis, by contrast, involves the interaction of metal ions with biomolecules secreted into the medium, where polysaccharides, peptides, or secondary metabolites mediate reduction and stabilization [1,15–18]. Both pathways present distinct advantages: intracellular synthesis often yields highly regulated nanoparticles with narrow size distributions, while extracellular synthesis simplifies downstream processing.

Several species, including *Chlorella vulgaris* and *Nannochloropsis oculata*, have demonstrated the ability to biosynthesize silver and gold nanoparticles, with properties modulated by factors such as pH and light intensity [14,19,20]. Extremophilic microalgae like *Galdieria sulphuraria* exhibit robust nanoparticle biosynthesis even under acidic and thermal stress conditions [11]. The biologically produced nanoparticles often possess unique surface properties, naturally coated with organic biomolecules, which enhance stability and potentially impart additional functionalities, such as selective catalytic activity [16,17]. These microalgal nanoparticles find applications across diverse sectors, including environmental remediation, antimicrobial coatings, biosensors, and energy storage materials. Their biological origin and benign synthesis pathways are increasingly aligned with regulatory and market demands for sustainable nanotechnologies. Integrating nanoparticle biosynthesis into bioremediation workflows creates a dual-functionality system wherein

microalgae simultaneously remove pollutants and produce high-value materials. This approach strengthens the economic feasibility of algal systems and exemplifies circular economy principles by transforming liabilities into assets. However, achieving controlled nanoparticle size, shape, and surface chemistry remains a technical challenge [21]. Scaling extracellular synthesis processes, ensuring nanoparticle stability, and standardizing product quality are critical research areas. Furthermore, comprehensive life-cycle assessments are necessary to rigorously quantify the environmental benefits of microalgal, nanoparticle production compared to conventional approaches.

## 4. From Biomass to Bioproducts: Green Extraction and Cascading Valorization

Following remediation or nanoparticle biosynthesis, microalgal biomass remains a valuable resource containing numerous bioactive compounds. Rather than relegating this residual biomass to low-value applications such as animal feed or compost, cascading valorization strategies can unlock multiple product streams. Lipids for biodiesel and nutraceuticals, pigments like astaxanthin and lutein for cosmetics and food industries, proteins for functional foods and feed, and carbohydrates for bioplastics or bioethanol are among the many bioproducts recoverable from algal biomass [22,23]. A cascading valorization approach enhances process economics by maximizing the utility of each biomass component while aligning with circular economy objectives.

Historically, the extraction of these biomolecules has relied heavily on organic solvents such as hexane, chloroform, and methanol. While effective, these solvents pose environmental and health risks, complicate recovery, and contribute to a significant ecological footprint. The advent of green extraction technologies, such as ionic liquids (ILs), deep eutectic solvents (DES), and supercritical carbon dioxide (SC-$CO_2$) extraction, provides sustainable alternatives that offer improved selectivity, safety, and integration into environmentally responsible processing chains [24–26]. Ionic liquids, comprising tailored combinations of organic cations and anions, exhibit high solvent power for diverse biomolecules. Their ability to penetrate microalgal cell walls and solubilize lipids and pigments under mild conditions preserves the bioactivity of target compounds while enhancing recovery yields [25,27]. Deep eutectic solvents, formed from benign components such as choline chloride and glycerol, have demonstrated comparable extraction efficiencies for pigments and fatty acids, providing an eco-friendly and biodegradable option [25,28]. Supercritical $CO_2$ extraction presents another compelling approach, particularly for non-polar compounds such as lipids and carotenoids. This method operates under relatively low temperatures, produces residue-free extracts, and facilitates efficient solvent recovery, making it particularly suitable for food-grade and pharmaceutical applications [29].

Incorporating green extraction methods into microalgal processing chains can enable a fully integrated valorization strategy. In an optimized system, microalgae would first sequester metals and nutrients, then facilitate nanoparticle biosynthesis, followed by the extraction of green solvents for bioactive compounds, with the residual biomass utilized for biofertilizer production, biochar production, or anaerobic digestion. This sequential utilization increases overall value recovery, minimizes waste, and strengthens the sustainability profile of microalgal bioprocessing [30]. Economically, cascading valorization diversifies revenue streams, reducing reliance on volatile biofuel markets and improving the return on investment for microalgal systems. It should be acknowledged that these economic benefits are theoretical in this context. We have not conducted a detailed techno-economic or market analysis, so claims of improved viability through cascading valorization remain speculative. Future studies will need to quantify production costs, revenue from co-products, and market dynamics to confirm that a multi-product, microalgal biorefinery truly enhances eco-

nomic feasibility. Environmentally, the adoption of green solvents and waste minimization substantially lower the ecological footprint of algal biorefineries. The design of integrated processes should ensure compatibility between stages [31]. For instance, nanoparticle biosynthesis should not adversely impact the recovery of downstream products. Similarly, the choice of solvents and extraction conditions should preserve the quality of residual biomass for secondary applications [32]. In practice, there may be trade-offs among these functions. For instance, heavy metal accumulation can impose stress on microalgal cells, potentially reducing growth or the yield of valuable biomolecules. If residual metals remain in the biomass, specific downstream uses (such as nutraceutical or feed applications) could be precluded due to contamination. Therefore, any integrated process should be optimized so that metal sequestration and nanoparticle formation do not irreversibly compromise cell viability or the quality of biomolecules intended for extraction. Strategies like selective metal desorption before biomass processing or using metal-tolerant algal strains may be necessary to balance these competing objectives. Moreover, it should be acknowledged that these economic benefits are theoretical in this context. We have not conducted a detailed techno-economic or market analysis, so claims of improved viability through cascading valorization remain speculative. Future studies will need to quantify production costs, revenue from co-products, and market dynamics to confirm that a multi-product, microalgal biorefinery truly enhances economic feasibility [33–35]. A systems-level approach to microalgal bioproduct recovery is thus essential for realizing the full potential of these organisms as sustainable production platforms.

## 5. Engineering Microalgal Systems for Multifunctionality

Realizing the concept of microalgae as environmental nano-factories will require innovation not only at the biological level but also in system design and operation. Conventional cultivation systems, such as open ponds and photobioreactors optimized primarily for biomass production, are insufficient for the demands of integrated bioremediation, nanoparticle biosynthesis, and cascading bioproduct extraction [36]. Emerging approaches focus on modular reactor designs capable of supporting distinct process phases—such as metal sequestration, nanoparticle synthesis, and biomolecule extraction—either independently or in integrated configurations. The application of selective membranes, for example, can enable the continuous separation of nanoparticles and metabolites, reducing reliance on energy-intensive downstream processing [1,37]. Multi-phase reactor systems capable of supporting gas, liquid, and supercritical extraction phases concurrently present promising avenues as well. Integrating supercritical $CO_2$ extraction chambers within bioreactors could enable in situ product recovery while maintaining culture viability, minimizing process interruptions, and reducing energy inputs. The integration of real-time monitoring technologies is central to maintaining system stability and optimizing performance. Advanced sensor networks capable of measuring metal ion concentrations, nanoparticle synthesis kinetics, photosynthetic parameters, and metabolite profiles provide the necessary data for controlling dynamic systems. Machine learning algorithms applied to this data could allow predictive adjustments to light regimes, nutrient delivery, and flow rates, enhancing reactor efficiency and robustness. The concept of "smart bioreactors" thus emerges as a critical enabler of multifunctional algal platforms [38].

On the biological front, synthetic biology offers valuable tools for strain engineering. CRISPR/Cas9 genome-editing techniques have been applied to *Chlamydomonas reinhardtii* to enhance lipid productivity, metal tolerance, and stress resilience [39–42]. Extending these capabilities to extremophilic species such as *Galdieria sulphuraria* would significantly broaden the operational range of engineered systems, enabling operation in environments that would be prohibitive for conventional strains [9]. Furthermore, targeted metabolic

engineering could optimize nanoparticle biosynthesis pathways, secretion of valuable metabolites, or confer enhanced tolerance to toxic conditions. Beyond monocultures, the engineering of synthetic microbial consortia offers additional benefits. In natural ecosystems, microalgae coexist with bacteria in mutualistic relationships that enhance nutrient availability, stress tolerance, and metabolic diversity [42,43]. Replicating or enhancing these interactions can improve system resilience and functionality. For example, nitrogen-fixing bacteria could supply bioavailable nitrogen, while algae supply oxygen, creating a self-sustaining microenvironment. Certain bacteria may also assist in nanoparticle stabilization or contribute to the degradation of complex pollutants [44]. Collectively, innovations in reactor architecture, dynamic control systems, strain engineering, and microbial consortia design represent the foundational components of next-generation microalgal nano-factories. However, realizing this potential will require coordinated advances across disciplines, new funding models that support high-risk technological development, and regulatory frameworks that accommodate the novel products and processes emerging from these systems.

## 6. Challenges, Knowledge Gaps, and Strategic Recommendations

Despite the promising advances outlined, significant challenges remain in fully realizing the vision of microalgae as multifunctional, environmental nano-factories. Scalability remains a primary barrier. Industrial-scale cultivation of microalgae is hindered by persistent challenges, including contamination control, limited light penetration, suboptimal gas exchange, and the energy-intensive nature of harvesting processes [45]. Large-scale algal cultivation must be carefully managed to prevent uncontrolled growth, which could result in biofouling of cultivation equipment and potential eutrophication in adjacent water bodies. Effective management strategies include controlled nutrient delivery, regular biomass harvesting, and engineered containment measures. Implementing predictive modeling tools and real-time monitoring can also significantly mitigate these risks by maintaining optimal cultivation conditions and ensuring process stability. While innovations such as biofilm reactors and self-flocculating strains offer potential improvements, their broad commercial application remains limited. Maintaining stable, high-performing cultures in open, non-sterile environments remains economically and technically challenging. In dense cultures, achieving uniform light distribution and optimizing carbon dioxide delivery while preventing oxygen buildup remain critical challenges in reactor design [46]. Beyond technical hurdles, regulatory and societal acceptance issues represent additional obstacles. Although biosynthesized nanoparticles derived from microalgae offer clear sustainability advantages, they are likely to face stringent regulatory scrutiny concerning their environmental fate and human health impacts. Similarly, genetically modified microalgae, even when deployed in contained bioreactor systems, may encounter resistance from the public and policymakers rooted in broader concerns about genetically modified organisms (GMOs) [47]. Clear, science-based regulatory frameworks tailored to the specific characteristics of microalgae-based nanotechnologies are urgently needed. However, overcoming public and regulatory barriers is not simply a matter of better communication. Societal concerns surrounding the release of genetically modified algae and nanoparticles involve complex cultural, ethical, and political dimensions. Public wariness may persist even with transparent engagement, as it often stems from underlying values and historical context (not just a knowledge gap). For example, field trials of genetically engineered algae were met with community opposition and legal challenges, illustrating that concerns may persist despite transparent communication efforts [48]. Moreover, it is telling that no fully integrated microalgal 'nano-factory' has yet to be deployed commercially, a reminder that these regulatory and acceptance challenges, alongside technical hurdles, remain unresolved in real-world practice. Any path forward will need to grapple with

these realities, working within robust regulatory frameworks and societal dialogs that address genuine safety and ethical considerations [49]. Although biosynthesized nanoparticles avoid the use of toxic chemicals in production, the nanoparticles themselves are not inherently benign. Emerging studies indicate that even 'green' silver nanoparticles can exert toxic effects in aquatic ecosystems, impacting organisms across trophic levels [50–54]. Algae-extracted nanoparticles, despite their biological origins, have been shown to negatively affect aquatic organisms, beneficial soil microorganisms, and plants at relatively low concentrations [52,53]. Such findings highlight the potential for bioaccumulation and ecological risks, underscoring the need for thorough ecotoxicological assessments of biologically synthesized nanomaterials. Accordingly, this manuscript tempers any implication that green-synthesized nanoparticles are automatically safe and emphasizes that rigorous toxicity and fate evaluations are necessary before environmental release. Early, proactive engagement with stakeholders, including policymakers, industry representatives, and the broader public, will be important to foster trust and ensure responsible innovation.

At the fundamental scientific level, key knowledge gaps remain. The molecular mechanisms governing heavy metal uptake, intracellular trafficking, and nanoparticle nucleation in microalgae, particularly in extremophilic species such as *Galdieria sulphuraria*, are not fully elucidated [10,11]. Without a mechanistic understanding of these processes, efforts to optimize biosynthesis through genetic engineering or process modifications will remain largely empirical. Furthermore, the potential long-term ecological impacts of releasing biologically synthesized nanoparticles into natural ecosystems are poorly characterized, underscoring the need for comprehensive ecotoxicological assessments. Sustainability assessment also remains underdeveloped. Although microalgal systems are often positioned as environmentally superior alternatives, few studies have conducted rigorous life-cycle analyses (LCAs) quantifying resource inputs, energy consumption, greenhouse gas emissions, and net environmental impacts relative to conventional technologies [33,35,55,56]. Without standardized LCA methodologies tailored to the complexities of integrated microalgal systems, claims regarding sustainability will remain speculative.

Strategically, several actions are necessary to advance the field. Future investments should prioritize the development of modular, adaptive bioreactor designs capable of supporting multifunctional operations. Synthetic biology toolkits should be expanded to enable precise metabolic engineering of extremophilic and non-model algal species. Research into engineered algal–bacterial consortia should be supported to exploit natural mutualisms and enhance system resilience. Green extraction and cascading valorization strategies should become standard practice, shifting focus from maximizing biomass yield alone to maximizing overall value recovery within environmentally responsible frameworks. Finally, interdisciplinary research hubs that integrate microbiology, materials science, environmental engineering, and economics are needed to foster holistic innovation. These hubs should work closely with regulatory bodies and maintain proactive public engagement to ensure that technological advances align with societal needs and expectations. Although integrating complex processing methods, particularly those involving advanced nanotechnological innovations, poses significant technical and regulatory challenges, current trends in research and pilot-scale projects suggest a realistic horizon of approximately 10–15 years for broader commercial and industrial deployment. This timeframe can be shortened through increased interdisciplinary collaboration, strategic funding for scale-up demonstrations, and proactive regulatory engagement. The opportunity space for microalgae as environmental nano-factories is considerable. However, capturing this potential will require strategic vision, interdisciplinary collaboration, and a sustained commitment to sustainability and inclusivity across all stages of research and development.

## 7. Conclusions

The repositioning of microalgae within the broader landscape of environmental science, biotechnology, and sustainable industrial innovation is timely and warranted. Microalgae should no longer be perceived solely as passive biomass producers or niche bioremediation agents. Instead, they should be recognized as dynamic, multifunctional, living nano-factories capable of addressing complex environmental challenges, synthesizing high-value nanomaterials, and supporting the transition toward regenerative economic models. Realizing this expanded role requires a paradigm shift from linear, single-product development models toward integrated, multifunctional, and sustainability-centered frameworks. Multifunctionality, modular system integration, and rigorous life-cycle sustainability assessment should become central design principles for sustainable development. Achieving this transformation requires strategic investments in engineering innovation, synthetic biology, and interdisciplinary research. Equally important is the development of robust, adaptive regulatory frameworks and early, transparent engagement with diverse stakeholders to foster responsible and equitable technological deployment. Ultimately, microalgae offer a tangible, scientifically grounded pathway toward a more resilient and regenerative future. By unlocking their full multifunctionality, it may become possible to simultaneously address environmental degradation, resource scarcity, and industrial sustainability challenges. Through biological ingenuity and strategic systems design, waste can be transformed into wealth, pollution can be converted into products, and environmental stewardship can be leveraged into economic opportunity. Even waste and pollution can potentially be converted into valuable products, linking ecological stewardship with economic opportunity. The concept of microalgae as 'living environmental nano-factories' is still emerging. Carefully exploring this potential, with an evidence-based approach, could contribute to a more sustainable future, but realizing it will require ongoing research and pragmatic evaluation.

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